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AMERICAN GEOPHYSICAL UNION

TRANSACTIONS OF 1942

PART I
REPORTS AND PAPERS
JOINT REGIONAL MEETINGS
SECTION OF HYDROLOGY

(A) DALLAS, TEXAS
(B) PASADENA, CALIFORNIA

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PREFACE

The American Geophysical Union was established in 1919 as the American Committee of the International Union of Geodesy and Geophysics, and its Executive Committee on Geophysics of the National Research Council. The objects of the Union are to promote the study of problems concerned with the figure and physics of the Earth, to initiate and coordinate researches which depend upon international and national cooperation, and to provide for their scientific discussion and publication. In the accomplishment of these objects, the Union is divided into Sections following the plan of organization of the International Union of Geodesy and Geophysics. There are now eight Sections, namely, (a) Geodesy, (b) Seismology, (c) Meteorology, (d) Terrestrial Magnetism and Electricity, (e) Oceanography, (f) Volcanology, (g) Hydrology, and (h) Tectonophysics. A Section of Geophysical Chemistry was discontinued May 31, 1924, as the International Union had failed to provide such a Section. The Section of Hydrology was established November 15, 1930--matters pertaining to scientific hydrology referred to the American Geophysical Union had been previously looked after by special committees on Hydrology. The Section of Tectonophysics was established April 9, 1940, for the purpose of promoting and encouraging research of fundamental importance to our knowledge of Earth-structure not covered in any one of the other Sections of the Union.

General assemblies of the Union and meetings of its Sections for presentation and discussion of papers and symposia are held in Washington, D. C., each year. The first annual meetings were those of 1920. Following the formation of the Section of Hydrology, Regional Meetings have been held usually in joint sessions with other organizations having coordinated interests. For the purpose of such meetings, the Executive Committee of the Section of Hydrology designated selected Regional Areas and their territories, namely: North Continental Divide--Montana, Idaho, eastern Washington, Oregon, and Alberta (affiliated); South Continental Divide--Colorado, Wyoming, Utah, and New Mexico; North Pacific Coast--western Washington, Oregon, Alaska, and British Columbia (affiliated); South Pacific Coast--California, Nevada, Arizona, and Hawaii. Besides the Regional Meetings sponsored by the Section of Hydrology, the Union has also encouraged joint meetings with organizations and societies interested in the discussion of various aspects of the geophysical sciences.

A complete list of Regional Meetings held prior to those reported upon in this volume will be found on page 3 of the "Transactions of 1941."

The present volume, Part I, "Transactions of 1942" [pp. 1 to 171], contains (a) the papers of the Joint Meeting with the American Association for the Advancement of Science at Dallas, Texas, December 30, 1941 [pp. 5 to 56], and (b) the papers, discussions, and reports of Research-Committees at the Regional Meeting of the South Pacific Coast Area at Pasadena, California, January 16 to 17, 1942 [pp. 59 to 148], jointly with the Western Interstate Snow-Survey Conference [pp. 149 to 168].

The general officers of the American Geophysical Union for the meetings reported upon in this volume were: President, W. C. LOWDERMILK; Vice-President, L. H. ADAMS; General Secretary, J. A. FLEMING. List of the officers of the Section of Hydrology and of the Regional Meeting are given on page 59.

The costs of publication for the proceedings reported upon in this volume were provided by the American Geophysical Union. The preliminary editing of the manuscripts was done by A. N. SAYRE for the Dallas Meeting, and by FRANKLIN THOMAS and W. A. LANG, F. H. PAGET, and J. E. CHURCH for the Pasadena Meeting. The final editing and preparation of master-copy were done by J. A. FLEMING and J. J. CAPELLO, General Secretary and Assistant Secretary, respectively, and by W. E. SCOTT, of the American Geophysical Union. We are indebted to W. C. HENDRIX for the necessary redrawing and photographing of the illustrations. As in past years, the excellent offset printing of the master-copy was done by the Kirby Lithographic Company, Inc., of Washington, D. C.

The importance and wide spread of the general field of Hydrology are once more emphasized by the reports and discussions presented in this volume. They manifest that effort toward coordination and collaboration of kindred interests in geophysics so preeminently the function of the Union in the investigation of the Earth sciences.

J. A. Fleming, General Secretary,
American Geophysical Union

SECTION OF HYDROLOGY
AMERICAN GEOPHYSICAL UNION

REPORTS AND PAPERS

JOINT REGIONAL MEETING
WITH AMERICAN ASSOCIATION FOR THE
ADVANCEMENT OF SCIENCE
DALLAS, TEXAS
DECEMBER 30, 1941

Published August 1942

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SYMPOSIUM ON RELATION OF GEOLOGY TO THE GROUND-WATER PROBLEMS OF THE SOUTHWEST

(A symposium presented under the joint auspices of the Section of Hydrology of the American Geophysical Union, the Geological Society of America, and Section E of the American Association for the Advancement of Science at Dallas, Texas, December 30, 1941)

INTRODUCTION

Allyn C. Swinnerton

Water has been commonly regarded as "free as air". Increasing recognition of ground-water as a resource which requires conservation and wise utilization gave both scientific and popular appeal to the joint meeting of the American Geophysical Union, the Geological Society of America, and Section E of the American Association for the Advancement of Science. The session, one of a series of symposia on the Geology and Geography of the Southwest, was held Tuesday morning, December 30, 1941, in room 616 of the First Baptist Church of Dallas, Texas, during the one hundred and tenth annual meeting of the American Association. Dr. Charles N. Gould, retired director of the Geological Survey of Oklahoma, presided. Attendance passed the one hundred mark.

Mr. Meinzer's introductory paper describes the organization of the investigation of ground-water in the Southwest, the extent of the work and the personnel involved, and discusses briefly the ground-water provinces together with the typical problems of each region.

Mr. Broadhurst's investigation of the utilization of the water-supply of the High Plains in Texas indicates that the principal source of fresh water is the Ogallala formation and what the balance is between discharge, recharge, and pumpage. For a somewhat larger region Mr. Burleigh concludes that the ground-water data show little opportunity for further agricultural expansion. More effective use of water and more precise knowledge of the behavior of the aquifers are the next steps in adequate use of the area's resources.

The hydrologic system of the Edwards-Georgetown limestone reservoir, reported by Sayre and Bennett, shows evidence of ground-water movement from the recharge-areas not only down-dip but also diagonally. This limestone reservoir is very productive, yielding artesian springs and wells which are among the largest known. Probably the artesian well of greatest volume in the world is in this area.

An artesian system and its effects in soluble rocks is described by A. M. Morgan. The Pecos Basin, with its great thickness of limestones, gypsum, and halite, is supplied by a limestone aquifer. Circulation to the surface has dissolved vast quantities of salt and gypsum and is, according to Morgan, responsible for the development of the Pecos depression. Solution of salt and anhydrite at depth by artesian circulation is shown by Frye and Schoff to account for the sink-holes of the Meade Basin of Kansas and Oklahoma.

Mr. Guyton's paper on the results of measuring the transmissibility of the Carrizo sand illustrates current attempts to reduce ground-water studies to a precisely quantitative basis. The Carrizo sand is uniquely suitable for this purpose and the observational and theoretical results agree closely.

What happens when storm-waters cross a typical desert wash, and the probable effect on recharge of a flood-control dam are described in the final paper by Babcock and Cushing.

Discussion at the session was conducted informally and no abstracts were made of comments and remarks. A strong point was made of the general absence of knowledge of fundamental hydrologic principles both among laymen and in instructional institutions. Mr. Meinzer called attention to the forthcoming National Research Council volume in the Physics-of-the-Earth series, Hydrology, as an important aid for general educational purposes and reference.

Another point of discussion centered around the recognition of ground-water as an exhaustible resource and the consequent need for conservation-measures. Illustrations were cited both of desirable and undesirable practices. Comment was also made on the progress toward quantitative

results, and the factors which promoted and interfered with obtaining precise agreement between observation and theory.

The idea of the Symposium was conceived at the meetings of the American Geophysical Union in Washington in 1941. As a result of conferences between officers of the Union, Section E, and the United States Geological Survey, a committee consisting of three Union members--A. N. Sayre (Chairman), C. V. Theis, and S. W. Lohman--was appointed to set up the Symposium and invite the speakers. The organization of the program was handled in excellent fashion by the Committee, and the objectives set as the goal of the session were largely attained.

This Symposium follows several years of very cordial relations between the American Geophysical Union and Section E of the American Association for the Advancement of Science. The value of such cooperative undertakings is unquestioned and a continuation of relations in the future may well be anticipated.

Antioch College,
Yellow Springs, Ohio

GROUND-WATER STUDIES IN THE SOUTHWEST

Oscar E. Meinzer

(Published with the approval of the Director, Geological Survey,
United States Department of the Interior)

Geologists are concerned with the rock-systems that form the crust of the Earth. The ground-water geologists are concerned with the rock-systems specifically because the open spaces which the rocks contain serve as reservoirs and conduits for water--water which performs a large part of the geologic work that is in progress today and has been in progress during past ages; water which affects profoundly the whole hydrologic cycle and is still the principal source of water-supply for mankind, as it has been for primitive man and the other land animals before the time of artificial waterworks.

The ground-water geologist is concerned with these great, stable, natural systems of waterworks as a hydraulic engineer is concerned with artificial systems of waterworks. The engineer designs, constructs, and operates his systems of waterworks, whereas the ground-water geologist finds the natural waterworks already constructed and in operation when he appears upon the scene. The ground-water geologist, however, studies the construction and operation of the natural waterworks and, with the knowledge thus acquired, he finds ways to modify their operation so as to increase the water-supplies, put them to more valuable uses, and conserve them so that adequate supplies will be available at all times.

Most geologists who are specialists in specific mineral products of economic value find that their field of operation is limited to certain terranes in which such products occur. The ground-water geologists, however, find that their services are required in every State of our Union, in every country on Earth, and on the islands of the sea; they find themselves working on rocks of every type, on nearly every kind of rock-structure, and on every rock-system from the pre-Cambrian to the Quaternary. The comprehensive character of the ground-water work is due to the combination of four conditions, namely, the world-wide distribution of the precipitation which provides the ground-water, the general occurrence of pores, joints, or other openings in rocks of nearly all kinds, the universal and imperative need of man for water-supplies, and the economic impracticability of transporting this bulky product for long distances.

While the study of the ground-water involves almost the entire field of geology, it is evident that it involves a good deal more. It must already have occurred to you that in the study and operation of any waterworks, natural as well as artificial, the talents of the hydraulic engineer are required. But because of the small sizes of the pores and most other openings in the rocks, adhesion and friction have important effects in the operation of the natural waterworks which are essentially different from anything that occurs in the operation of artificial waterworks. Different principles of physics are involved. Moreover, the water, in its intimate contact with the rocks, takes much of the rock-material into solution, and consequently processes of chemistry are involved. Thus the study of the ground-water is conducted by geologists, engineers, physicists, and chemists. It is a branch of the science of hydrology, with distinctive subject-matter and technique.

The principal program of ground-water studies in the United States is that of the United States Geological Survey in cooperation with State Geological Surveys and other State bureaus concerned with water-resources and, to some extent, with cities and counties. This program requires the services of about 100 technical men, not including assistants of sub-professional grade; it involves the expenditure of about half a million dollars annually. Much ground-water investigation is, of course, also accomplished by other public and private organizations, too numerous to mention.

The Geological Survey cooperates with nearly all the Southwestern States in ground-water work. The programs in Arkansas, Louisiana, Kansas, Oklahoma, Texas, New Mexico, Arizona, and California have an aggregate staff of about 50 technical men and a total budget in the current fiscal year of about $270,000. The respective budgets for these States are about as follows: Texas, $79,000; Kansas, $62,000; California, $42,000; Arizona, $38,000; New Mexico, $21,000; Louisiana, $14,000; Oklahoma, $10,000; and Arkansas, $4,000.

The Southwest includes parts of several important ground-water provinces. Investigations are in progress in all of these provinces, and nearly all are represented by papers in this Symposium.

The Gulf Coastal Plain and Mississippi embayment have many large supplies of ground-water, derived chiefly from a succession of sand-strata interbedded with clayey strata, generally with artesian structure. The average daily pumpage in some of the most productive areas in the Coastal Plain of Texas are as follows:

Average daily pumpage (in gallons) in the Coastal Plain of Texas in 1940

Houston-Pasadena District	81,000,000
Katy District	45,000,000
Galveston District	21,000,000
Lufkin District	5,000,000
Rice-growing areas outside of the Katy District	35,000,000
Winter Garden	
Dimmit and Zavala counties	20,000,000
Frio, Atascosa, and Uvalde counties	8,000,000
Total	215,000,000

In Arkansas the pumpage for rice-irrigation has been equivalent in recent years to about 160,000,000 gallons a day. In Jefferson Davis and Acadia Parishes, Louisiana, the pumpage in 1939 was estimated to have been equivalent to about 275,000,000 gallons a day, and the total pumpage in Louisiana for irrigation may amount in some years to as much as an average of 450,000,000 gallons a day. In 1941, however, the pumpage in all the rice-areas has been less because of the heavy precipitation.

The primary problems in this province are concerned with the rate at which water is naturally transmitted from the outcrops or other intake areas to the pumped areas and the maximum rate that can be maintained perennially if the cones of depression are developed as much as practicable. Related are the problems as to the quantities of water taken out of storage with the release of artesian pressure, the sufficiency of the recharge at the intake areas to permit the quickened transmission (produced by pumping) without lowering of the water-table, and the danger of drawing in salty water from the sea, from the salt domes, or from the salt-water beds which underlie the pumped areas or are interbedded with the strata that produce the fresh water. Mr. Guyton's paper outlines one of a number of intensive investigations that have been or are being made in this ground-water province.

The limestones of the Edwards Plateau and bordering Balcones fault-zone present very different geology and accordingly very different ground-water conditions. Of outstanding interest are the first magnitude springs and the very productive artesian wells. Comal Spring, the largest in this region, has an average discharge of more than 200,000,000 gallons a day, and an artesian well near San Antonio was recently brought in with a record natural flow of about 25,999,000 gallons a day. Where the limestone is cavernous it has great intake capacity and also delivers water in great quantities to springs and wells. But the limestone is not everywhere cavernous and in some places it is underlain and overlain by strata that are relatively impervious; moreover, the whole rock-system is traversed by a complex of faults which dam the ground-water and yet afford conduits that lead the water long distances parallel to the faults. The close relation between the

geology of this region and the unusual behavior of its ground-water is shown in the paper by Sayre and Bennett. It is of great practical importance because ground-water or surface-water developments in one place may take away the water-supply from some distant place whose hydrologic connection would not ordinarily be suspected.

The High Plains have long had an enviable reputation and a nation-wide publicity for their copious and perennial supplies of potable ground-water, which has been the principal comfort and hope of the settlers during many years of parched land and crop-failures--their comfort for drinking, household use, watering live stock, and irrigating gardens and trees for fruit and shade; their hope in either conservative or grandiose schemes for field-irrigation.

The theory that the ground-water of the High Plains is derived by percolation from the Rocky Mountains gripped the imagination of the settlers and has not wholly lost its grip in spite of the contrary evidence produced by the geologic studies. The recent studies have shown that the ground-water generally occurs under water-table conditions, that there are large quantities of water in storage, and that the rates of recharge over large parts of the High Plains are relatively small although in certain parts there is heavy recharge. On the High Plains in Texas the recharge is relatively small, yet the pumpage for irrigation in 1940 was equivalent to an average throughout the year of about 200,000,000 gallons a day. However, the reservoir is so large and the pumping is distributed over such a wide area that this heavy pumpage produced only a moderate lowering of the water-table during the year. In the Arkansas Valley in Kansas, however, large recharge has been demonstrated by the fact that there has been heavy pumping for irrigation since near the beginning of this century without causing notable depletion in the storage. The pumpage from wells in the Arkansas Valley in five counties in western Kansas from 1938 to 1940, for municipal, industrial, and irrigation purposes averaged about 60,000,000 gallons a day.

There are two papers on this interesting province--one by Burleigh and the other by Broadhurst.

The Basin and Range Province has a water regimen entirely different from any of the three that have already been mentioned. Its bolson deposits have great storage-capacity, with partly water-table and partly artesian conditions. The recharge is derived chiefly from water that flows out of the mountain ranges over the alluvial fans. Where the mountains are low and the climate arid the recharge may be very small, but in the most favorable areas it is very great. In some of the valleys of southern California there has been heavy pumping from wells for many years and it has been demonstrated that the recharge, especially in wet winters, is exceedingly large.

In the Santa Ana River Valley, including the eastern coastal plain, the average ground-water pumpage is in the order of 300,000,000 gallons a day; of this amount a considerable part, however, has been supplied from storage. In the San Gabriel River Valley, including the central coastal plain, the average ground-water pumpage is in the order of 150,000,000 gallons a day. The current water-levels indicate that in this valley nearly all the pumpage since 1918 has been supplied by recharge. The recharge in excess of pumpage during the last five years has been computed at an average rate of about 70,000,000 gallons a day, compensating for the depletion in earlier years.

There are many problems relating to the ground-water in this province, including the natural rates of recharge, the increase in recharge produced by use, the methods of artificial recharge, the storage-capacity for each foot of depth, and salt-water encroachment. The paper by Babcock and Cushing relates to the processes of natural recharge in one of the valleys of this province.

Most of the early geologists, like other people who traversed the dessicated surface of this vast province, had no idea of the copious supplies of potable water that occurred beneath them. However, as I explained in the paper on the Tularosa Basin [see 1 of "References" at end of paper], Robert T. Hill [2] in 1891 clearly outlined the conditions affecting the ground-water of the bolson valleys and called attention to the fact that the principal supplies in these valleys occur in the valley-fill, not in the older rocks.

Large parts of the Southwest lie in other ground-water provinces than those which have been mentioned and are underlain by older rocks--chiefly rocks ranging from Carboniferous to Cretaceous in age. The ground-water problems in these regions are numerous and varied.

The ground-water geologists have made valuable contributions on the solution of the great salt formations of the region--the hydrologic processes involved, the quantities of salt that have been removed, the rate at which solution is proceeding at present, and the effects that have been pro-

duced by the solution upon the rock-structure and geomorphology. The paper by Morgan and that by Frye and Schoff relate to this subject.

In some of the recent ground-water work intensive study of surficial formations having only meager water-supplies has been undertaken with a view to obtaining maximum recovery in times of drought. The question is essentially whether when a well fails the failure is due to general conditions or to local depletion in the vicinity of the well; further, if it is due to local depletion, how much available ground-water is still in storage in other parts of the area. It has been observed that during times of severe drought many pumped wells in these areas virtually fail while in the unused observation-wells in the same areas there is only a moderate lowering of the water-level. This contrast suggests that the failure may be due to local cones of depression rather than to general depletion of the formation.

This paper would not be complete without reference to the well-known Roswell Artesian Basin, which is of unique interest in several respects. It is an ideal text-book example of an artesian basin and was selected as the subject for two dioramas exhibited in the Interior Department. It is also the country's leading example of equitable and effective legal control and conservation of ground-water, accomplished as the result of thorough investigation, careful legislation, wise judicial decision, conscientious administration by the State Engineer, and intelligent cooperation by the local people.

In conclusion, it may be said that the outstanding feature of the ground-water is the great amount of hold-over storage that is available. The present trend, except in a few places, is to develop progressively larger supplies without much regard to the rate of recharge or the draft that is being made upon the water in storage. Because of the large quantities in storage, the effects of overdevelopment proceed gradually and are often not noticed for a long time. In many areas, however, the depletion will probably become acute in the not very distant future and will be manifested in the extreme lowering of water-levels or the encroachment of salt water. Eventually order will be established and efficient use will be made of the vast storage-capacity of the subterranean reservoirs. Then the ground-water supplies will be perennially secure, as they already appear to be, under present management, in the Roswell Artesian Basin. This desirable objective can only be attained if the ground-water studies are continued on a sound quantitative basis, and reliable records of pumpage and water-levels are obtained through a considerable period of years.

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U. S. Geological Survey,
Washington, D. C.

RECHARGE AND DISCHARGE OF THE GROUND-WATER RESERVOIRS ON THE HIGH PLAINS IN TEXAS

W. L. Broadhurst

(Published with the approval of the Director, Geological Survey, United States Department of the Interior)

Introduction

The High Plains in Texas occupy an area of about 35,000 square miles extending from the northern boundary of the Panhandle southward about 300 miles, and from the New Mexico line eastward an average distance of about 120 miles to a boundary which in most places is sharply defined by a bold escarpment several hundred feet in height.

The region is noted for its abundant supply of ground-water, most of which is found in the Ogallala formation, a sandy deposit lying at or near the surface throughout most of the region, and reaching a depth of between 200 and 300 feet. The Ogallala formerly extended over a much greater area, but it has been removed by erosion from much of the territory it once occupied. The areas in which it remains are the High Plains, which are bounded by prominent escarpments both on the

east and on the west, and are traversed in Texas by the Canadian River, which is deeply entrenched in the older rocks. The water-bearing sands of the Ogallala in both segments are cut off in all directions from any underground connection, except through the underlying older rocks which contain highly mineralized water unlike the fresh water in the Ogallala. The source of the fresh water, therefore, is within the High Plains themselves, and is from the rain and snow that falls on the surface of the Plains.

Several general investigations of the ground-water resources of the region have been made in the past, and during the last five years a more intensive investigation has been in progress as part of a survey of the ground-water resources of Texas by the State Board of Water Engineers in cooperation with the United States Department of the Interior, Geological Survey. A list of the reports accompany this paper.

Recharge or intake of ground-water

Most of the surface of the High Plains is underlain from depths of a few inches to ten feet or more by sediments that are cemented in varying degrees with calcium carbonate and usually called caliche. These deposits, where they are well cemented, tend to prevent the penetration of water that falls on the surface of the Plains. However, in some relatively small areas the sediments are poorly cemented or the caliche has been removed by solution and in such areas infiltration may occur in substantial quantities. The principal areas of infiltration apparently are the depressions which are occupied intermittently by ponds, sandy stream-beds and their adjacent flood plains, and sand-hill areas.

Recharge from depression-ponds--On most of the surface of the High Plains in Texas depressions, ranging from a few feet to 50 feet or more in depth and from a few hundred feet to a mile or more in diameter, occur at irregular intervals. In some areas these depressions average about one to each square mile. Following large rains with considerable runoff, ponds that cover from a few acres to 100 acres or more are formed in the depressions. After the heavy rains in the summer of 1937 and 1938 stake-gages were placed in several depression-ponds and the rate of decline of the water-surface was observed. Some ponds were found to dry up quickly, indicating that they were feeding into the underground reservoir, while others lost water slowly, and mostly by evaporation. Several hundred test-holes ranging in depth from 30 feet to as much as 100 feet were bored in these depressions in different parts of the High Plains. In some of them relatively little caliche was encountered, in others caliche was found all the way across the depression but was relatively soft, and in still others the caliche was so hard it could not be penetrated by the hand drill and was designated by the drillers as rock. A study was made of water-level fluctuations in numerous wells near depression-ponds. After heavy rains, which filled or partly filled the ponds, the water-level rose in most of the wells. The rise in some wells during several months after the rains was less than a foot, while in others it was several feet. In a few wells the rise following the phenomenally heavy rains of 1941 amounted to more than ten feet.

The hydrograph of well 542 (Fig. 1) near a depression in Hale County shows the rise of the water-level following rains in May and June 1937 and during the spring, summer, and fall of 1941. The depression was dry during most of 1938 through 1940.

Recharge from streams--From what has been said it will be understood that a large part of the High Plains has a poorly developed drainage-system. All of the streams that head on the Plains are intermittent or have a very small perennial flow. Following exceptionally heavy rains these streams carry large quantities of water; however, the storm-waters in some of them, such as Running Water Draw, Blackwater Draw, Sulphur Draw, and possibly others, seldom reach the eastern escarpment. For example, after heavy rains in May 1937, the discharge of Running Water Draw at Plainview reached a peak of 1,200 second-feet but the maximum flow 14 miles below Plainview was only about 80 second-feet. Most of the water was absorbed by the soil and a part percolated downward to the water-table. Rains of almost cloudburst intensity fell in western Bailey County near the head of Blackwater Draw in June 1938, but the water did not flow in the draw in Lamb County, 30 miles to the east. Numerous wells near streams have been measured at intervals and show substantial rise in water-levels after freshets. The hydrograph of Well 511, Hale County (Fig. 1), shows the abrupt change of the water-level in the well following heavy rains and a considerable flow of water in Running Water Draw.

Recharge in sand-hills--In parts of the region sand-hills and the adjacent areas of sandy soil probably afford the best opportunity for the infiltration of water, although, because of their limited areal extent, they probably do not contribute as much recharge in the aggregate as the sinks and

streams. These areas consist of relatively low hills in which there is little or no drainage, as practically all of the rain is absorbed by the sand. One area of sand-hills extends from the western escarpment of the High Plains eastward through Roosevelt County, New Mexico, to Hale County, Texas. Another large area begins in Lea County, New Mexico, and extends eastward to Lynn County, Texas. Sand-hill areas of less extent are present in Dallam, Hartley, Oldham, and other counties in the Panhandle. The hydrograph of Well 88 in the sand-hills of Lamb County (Fig. 1) shows the rise of the water-level in the well after heavy rains in 1939 and 1941.

Recharge in upland areas--The greater part of the surface of the High Plains in Texas consists of broad level high prairies which for convenience may be designated the uplands. Records of wells on the uplands during the last few years in areas remote from irrigation-pumping show relatively little fluctuations in water-levels. Recent measurements of water-levels have been made in 22 upland wells both north and south of the Canadian River in ten counties. Seventeen of the wells show a rise in water-levels during the last year, ranging from 0.03 foot to 0.90 foot and averaging 0.35 foot. The other five show a decline ranging from 0.01 foot to 0.70 foot and averaging 0.20 foot. The hydrographs of Well 825 Hale County and Well 231 Lamb County show typical water-level fluctuations beneath the uplands (see Fig. 1).

Discharge of ground-water

Natural discharge--In 1938 and 1939 studies of ground-water discharge were made along a 75-mile stretch of the escarpment extending southward from Quitaque Creek to Double Mountain Fork of the Brazos River, across parts of Briscoe, Floyd, Motley, Dickens, and Crosby counties. In these studies the springs and seeps were mapped and their discharge measured or estimated and estimates were made of the losses of ground-water by evaporation and transpiration from marshy areas created by the seeps which were not taken into account in the measurements. The discharge of ground-water was also estimated or measured on the Plains themselves in a segment

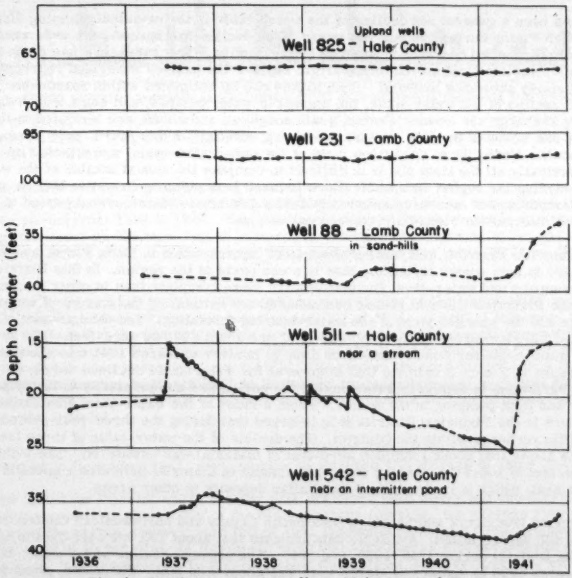

Fig. 1--Depth to water in wells in high plains of Texas

comprising about 9,000 square miles extending from this stretch of the escarpment northwestward to the western boundary of the Plains in New Mexico. In most of this segment the water-table is from 50 to 200 feet or more below the surface, the streams carry water only for a short time after heavy rains and are influent; that is, they contribute to the underground reservoirs. In some places, however, especially in the southeastern part of the segment near the escarpment the streams have cut below the water-table, marshy areas have developed along their banks and springs and seeps provide a small perennial flow. From all the data thus obtained it is estimated that the total natural discharge of ground-water along the 75-mile stretch of the escarpment investigated and in the segment of 9,000 square miles of the Plains back of it is at the rate of 25,000 to 30,000 acre-feet a year.

Discharge from irrigation-wells--Irrigation from wells in the High Plains in Texas was started near Plainview, Hereford, and Muleshoe about 30 years ago. It was moderately successful for a few years and by 1914 about 140 irrigation-wells had been completed. During the next 20 years there was comparatively little development. In 1934 the total number had reached about 300, many of which had been unused for years. Since then the rate of development has increased rapidly. Estimates of the number of wells pumped and the amount of land irrigated from them since 1937 are as follows: 1937, 1,150 wells pumped and 160,000 acres irrigated; 1938, 1,500 wells pumped and 200,000 acres irrigated; 1939, 1,700 wells pumped and 230,000 acres irrigated; 1940, 2,100 wells pumped and 280,000 acres irrigated. The amount of water, in acre-feet, withdrawn during the four years is roughly estimated as follows: 1937, 130,000; 1938, 145,000; 1939, 165,000; 1940, 190,000. In 1941 the rainfall was exceptionally heavy, the highest on record in parts of the region, irrigation was light except in the early spring, and only a few new wells were drilled. The amount of water withdrawn may not have exceeded 50,000 acre-feet. On the above basis, if it is assumed that the pumpage in 1941 was 50,000 acre-feet, the total withdrawals from 1937 to 1941 amounted to about 680,000 acre-feet.

The effects of pumping on ground-water in storage

There has been a general net decline of the water-table in the principal pumping districts of the Texas High Plains during the last few years. The decline has spread over wide areas and a large volume of material has been unwatered by the decline. The water that has drained out as the water-table declined has moved downward to replace the pumped water and represents a loss from the formerly saturated material. Such losses can be estimated within reasonable limits if the regional decline of the water-table, the amount of water pumped, and some knowledge of the magnitude of recharge are known. Cotton, grain sorghum, and alfalfa are irrigated in the spring and summer and wheat in the fall, winter, and spring, although in dry years there is some pumping every month. Under these conditions most of the observation-wells are affected by local pumping practically all the time and it is difficult to compute the annual decline of the water-table. Considering the region as a whole there is much less pumping in winter than in summer; therefore, comparison of measurements made during January to March over a period of years gives the best information regarding the regional decline.

In the Plainview District, comprising about 1,000 square miles in Hale, Floyd, and Swisher counties, there is less winter irrigation than in some parts of the region. In this District the records of pumpage and water-level fluctuations are more complete than in other pumped areas. Therefore, the Plainview District seems best adapted for estimating the amount of water taken from storage and the specific yield of the water-bearing formation. The total amount of water pumped in the District during 1938, 1939, and 1940 was about 300,000 acre-feet. The average decline of the water-table for January to March 1938 to January to March 1941 was about three feet. The hydrographs in Figure 2 indicate that in general the water-table declined during the last few years. The variations in depths to water during the period are due primarily to heavy pumping in the summer and light pumping in the winter. From a study of the water-level fluctuations and the rainfall-record in the Plainview District it is believed that during the three-year period there was relatively little recharge within the District. The decline of the water-table of three feet in 1,000 square miles shows that about 1,920,000 acre-feet of material was unwatered. The withdrawal of 300,000 acre-feet of water by pumping from this volume of material indicates a specific yield of about 15 per cent, which is comparable with similar deposits in other areas.

The Hereford District of southeastern Deaf Smith County and northwestern Castro County comprises about 400 square miles. Available data indicate that about 100,000 acre-feet of water was pumped in the District during 1938, 1939, and 1940. The average decline of the water-table for January to March 1938 to January to March 1941 was about 2.35 feet. Therefore, about 601,600 acre-feet of material was unwatered. If the specific yield is 15 per cent, approximately 90,000

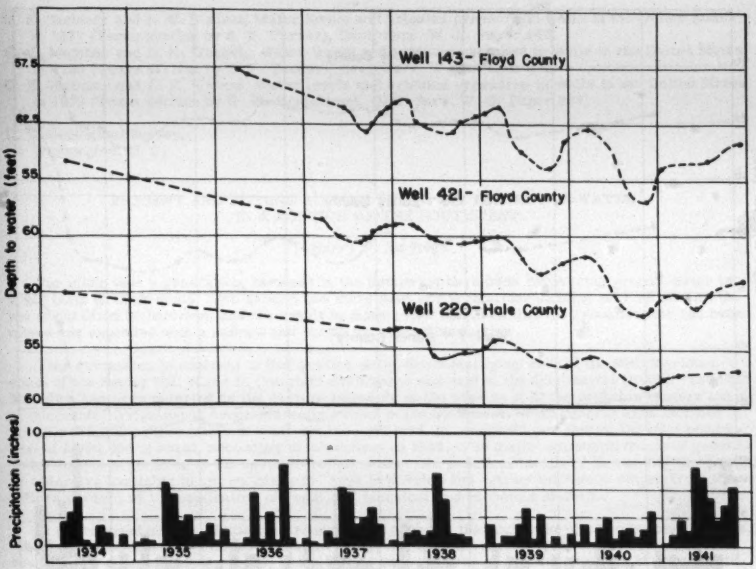

Fig. 2--Depth to water in wells in Plainview District and precipitation at Plainview, Texas

acre-feet of water was removed from storage within the pumped area. A very slight unwatering of the material around the outer edge of the irrigation-district could account for the remaining 10,000 acre-feet of water pumped.

In the Muleshoe District, comprising approximately 65 square miles, in northern Bailey County and northwestern Lamb County, about 30,000 acre-feet of water was pumped during the three-year period from 1938 to 1940. The average decline of the water-table was about 1.5 feet, indicating that about 62,400 acre-feet of material was unwatered. Assuming the specific yield to be 15 per cent in this area, only about 9,000 acre-feet of water was removed from storage in the District.

Effect of heavy rainfall in 1941--There was a general rise of the water-table in the pumping districts of the High Plains during the summer and fall of 1941. A part of this rise, doubtless, was due to the fact that the pumping during the season was light and ground-water moved in from outlying unpumped areas; but a part of the rise can be attributed to recharge which probably was greater than it has been in any year since 1915. The rise in the observation-wells of the Plainview District for January to March 1941 to November to December 1941 averaged about one foot, representing, with a specific yield of 15 per cent, an increase in storage of about 96,000 acre-feet within the District.

The average rise of the water-table in the Hereford District was about one foot for January to March 1941 to December 1941, representing an increment to storage of about 38,000 acre-feet.

In the Muleshoe District where the pumping has never been heavy and conditions for the intake of water are better than in any of the other pumping districts, the average rise in water-levels during the spring, summer, and fall of 1941 amounted to about 6.5 feet, representing, with a specific yield of 15 per cent, an increment of 40,000 acre-feet of storage beneath an area of 65 square miles. The hydrographs in Figure 3 show fluctuations in water-levels in wells and rainfall-record in the Muleshoe District.

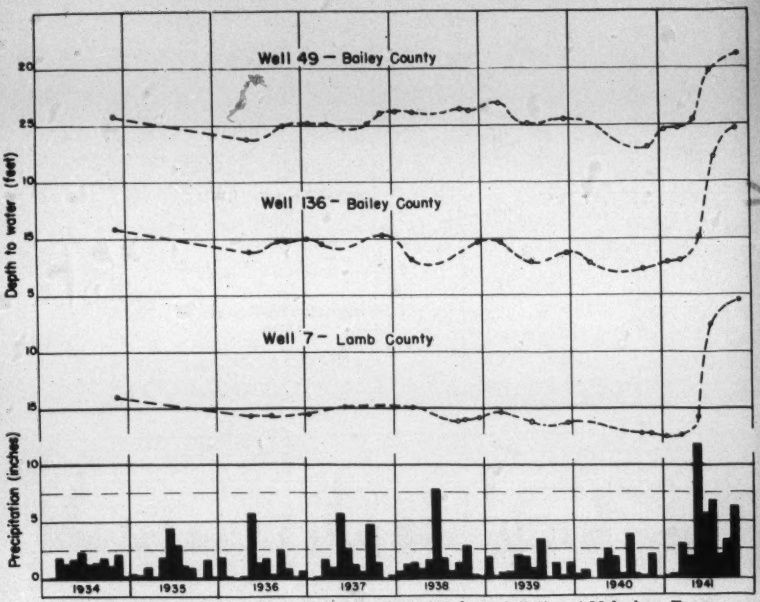

Fig. 3--Depth to water in wells in Muleshoe District and precipitation at Muleshoe, Texas

In the Texline District of northwestern Dallam County the estimated increment to underground storage during 1941 amounted to about 3,500 acre-feet.

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U. S. Geological Survey,
Washington, D. C.

PRESENT AND FUTURE AGRICULTURAL USE OF GROUND-WATER IN A PORTION OF THE SOUTHWEST

Harry P. Burleigh

For more than a generation, farmers in the Southwest have been recovering ground-water to apply them to their lands. Too seldom has there been any irrigation-planning carried on with the aid of qualified technicians, and the result in many cases has been that the ground-water has been mined and exploited with a narrow and injudicious objective in view.

This discussion is confined to that portion of the Southwest lying west of the 99th Meridian, south of the Smoky Hill River in Colorado and Kansas and east of the Continental Divide. The 99th Meridian has been selected as the eastern boundary of the area as it is the probable eastern limit of successful irrigation of crops normally raised in the Southwest. This general area includes roughly 326,000 square miles of semi-arid to arid land, in which 63 per cent of the total population of 2,309,000 is rural, according to the census of 1940. The major consumptive use of ground-water in this large area is for agricultural purposes. No practical means of increasing the supply of water are available to us; we can only hope to develop and extract maximum values from those waters present by the application of results of technical and economic studies.

It is proposed here to divide the ground-water areas in the Southwest into two general classes. The first class has two primary characteristics: (1) Ground-waters occur in the relatively narrow alluvial channels along rivers; and (2) their major source of recharge usually is the surface-discharge of the river coursing over the alluvium. In this class of ground-water areas, diversion of water-supply, either directly from the stream-channel or by pumping ground-water from the underlying alluvium, results in diminution of the surface of the discharge-basin. Six major streams, the Arkansas, Cimarron, Red, Pecos, Rio Grande, and Canadian rivers in this portion of the Southwest readily fall into Class I. These areas will be described later.

The second class of ground-water areas is defined here as those regions where: (1) The aquifer is exposed or underlies areas of considerable and irregular extent; and (2) the major source of recharge usually is a portion of the rainfall. The Southwest has six areas of this kind: The High Plains Physiographic Province; the Roswell Artesian Area in New Mexico; the San Luis Valley Area in south-central Colorado; the Mimbres Valley in southwestern New Mexico; Estacia Valley in Torrance County, New Mexico; and the portion of the Gulf Coastal Area, wherein the Carrizo and associated water-bearing sands occur close enough to the land-surface to enable profitable recovery of ground-water.

The distinction between the two classes is not too sharp but appears necessary, for consideration of the use of ground-waters of the alluvial areas necessarily is concerned with allied use of surface-discharge from the attendant stream. Use of ground-waters of the second class seldom has interfered legally with surface-water rights.

There are at least portions of 12 major areas in the Southwest in which ground-water can be pumped profitably for irrigation. These areas do not represent all localities where usable ground-water can be feasibly recovered for irrigation. Small areas which have possibilities for development, such as the shallow-water area between Balmorhea and Pecos, Texas, are scattered throughout the Southwest. However, estimates indicate that most of the future developments of ground-water irrigation in the Southwest will take place in these 12 areas.

All ground-waters occurring in Class I areas can be discussed as a whole because of the similarity in the manner of recharge and discharge to and from the alluvial aquifers. The major source of ground-water in the alluvial aquifers usually is the surface-flow of the stream. The

hydrologic conditions governing water-supply in the alluvium may vary from place to place along the stream-course; that is, in some places the stream-course may cross an aquifer from or to which the alluvium may receive or transmit water, or, in other places, it may traverse shales or other impervious rocks. However, generally the measured discharge of the stream will be essentially the total of the water available for irrigation. As the courts have held, both the surface- and ground-waters of such an hydrologic system must be treated as one.

A brief review of the hydrologic conditions governing ground-water supply in the six areas of Class II also is necessary.

The largest of the six areas in both size and quantity of well-irrigation development is the High Plains Area. Well-irrigation on the High Plains occurs in such widely scattered districts as the Plainview-Hereford, Muleshoe, and Texline areas in Texas, Lea County, New Mexico, and the Scott County Area in Kansas. The High Plains segments are all isolated hydrologic units in so far as ground-waters are concerned; and the only ground-waters available usually are those that originate within the High Plains.

Prior to artificial discharge, the natural ground-water recharge was approximately balanced by the natural discharge. Artificial discharge has resulted in lowering the water-table, at a rate partly dependent upon the rate of pumping, and the recovered water was obtained partly from storage. The declining water-table will lower the head and thus reduce the natural discharge, but the water-table may decline to a level below the limit of economic pumping before the effect of a lowered head upon natural discharge will be noticeable.

The ground-waters in the San Luis Valley occur both as unconfined and artesian waters in a broad intermountain fill. Both the shallow and artesian waters apparently are derived in considerable part from seepage of diverted surface-waters and therefore the replenishment to ground-water supplies in the area is directly related to the rate of surface-water diversion. The current ground-water withdrawal is negligible compared to the total supply and no decline in the water-table has become apparent in this valley.

The aquifer of the Mimbres Valley consists of a broad valley or intermountain fill with ground-water supplied in the upper end of the valley by seepage of surface-discharge. Pumping for irrigation has resulted in a declining water-table.

The Estancia Valley in Torrance County, Nex Mexico, is a topographic and structural basin. Apparently the natural discharge of the ground-water is through evaporation and transpiration. The major source of ground-water recharge is seepage from streams that converge into the basin. A moderately lowered water-table apparently would eliminate natural means of ground-water discharge, and irrigators then could recover ground-water to the amount of annual natural recharge without the fear of a continually lowering water-table.

In the artesian area centering around Roswell, New Mexico, ground-water has been obtained from a porous limestone aquifer. Well-conceived legislation has set up controls for the stabilization of the piezometric surface at a level where profitable recovery is still possible. It can be concluded that the current rate of water-production from the artesian aquifer is a permanent factor in the irrigation-economy of this area.

West of the 99th Meridian, Gulf Coast well-irrigation is largely centered in the Winter Garden Area. The Carrizo and associated sands outcrop south of the Balcones Escarpment and dip below the land-surface in the direction of the Gulf. The ground-water was originally confined under considerable hydrostatic pressure, and although artificial discharge of the ground-water has caused a great decline of head in the general Winter Garden Area, the head has been sufficient to permit economic recovery of waters for irrigation.

In each Class II area, prior to artificial ground-water recovery from various aquifers, an apparent hydraulic balance existed in which the rate of natural ground-water intake to the aquifers was balanced by the rate of natural discharge.

In the artesian areas, such as the Roswell and Winter Garden districts, the rate of pumping that can occur without an economically dangerous decline in piezometric surface has been measured by practical experience. Current ground-water recovery in the San Luis Valley Area--both free and confined water--appears to approximate the recharge. A considerably higher recovery, however, would probably produce a decline in the water-table and piezometric surface. As

ground-water in the San Luis Area is used only to supplement the surface-water supply, expansion of well-irrigation in this area does not appear to be a major problem. In an area such as the Estancia Valley Area of New Mexico, excessive decline in the water-table can be prevented by recovering no more than the annual recharge to the aquifer. The supposition is made that when ground-water use is fully developed, natural discharge would be eliminated by lowering the water-table below the zone of evaporation and transpiration. In the High Plains districts and in the Deming Area of New Mexico, recovered ground-water comes from partial storage, with the result that there is a constantly declining water-table.

To measure the effects of current ground-water usage against the previously outlined principles governing water-supplies in the various areas and to determine the effects of artificial discharge it is necessary to summarize generally current usage.

On the High Plains Area from the Smoky Hill River south, roughly 2,250 irrigation-wells are recovering currently 530,000 acre-feet of water per annum. (One acre-foot equals 325,851 gallons.) The rate of decline has varied widely, and although it has not become economically serious, intensified rates of water-recovery may result in a decline in the water-table sufficient to halt economic irrigation. During the last five years, practically all High Plains irrigation-districts have increased the rate of water-recovery by about 30 per cent per annum; a fact which must give all hydrologists and agriculturists concern.

In the Deming Area in the Mimbres Valley, New Mexico, available data indicate that the pumping rate is approximately 30,000 acre-feet of water annually. As a direct result of the considerably lowered water-table and increased costs of water, only those irrigators with better than average financial resources and managerial ability have continued to farm. On the basis of current pumping-costs and crop-prices it does not appear that irrigators in the Mimbres Area can pump water economically at a much greater head.

In the Estancia Valley Area in New Mexico there has been little development as yet, but preliminary estimates indicate that the ultimate safe rate of recovery may be somewhere between 18,000 and 24,000 acre-feet annually. In the Roswell (New Mexico) Artesian District, available data indicate that the present rate of recovery of approximately 150,000 acre-feet annually cannot be greatly exceeded without creating a decline in the piezometric surface that will be a distinct hazard to possible profit for many well-irrigators. Public opinion in the area apparently is firmly back of administrative control-measures.

In the Winter Garden Area, available data indicate that approximately 27,000 acres are irrigated by wells alone. On the basis of an average duty of approximately 1.3 feet, the average annual rate of water-production probably does not exceed 35,000 acre-feet. The recovery of this amount of water is apparently accomplished with no great fluctuation of the piezometric surface and it appears that the current pumping-rate can continue indefinitely.

Reasonably accurate data on annual withdrawal of ground-water are not available for the San Luis Valley Area in south-central Colorado. Available information indicates that approximately 151 pumping plants recover water from the unconfined aquifer. It is estimated that this pumping does not greatly exceed 14,000 acre-feet annually. It has been estimated that about 4,700 artesian wells discharge 110,000 acre-feet annually for agricultural use. One hundred twenty-four thousand acre-feet annually, therefore, appears to be a reasonable estimate of ground-water production in the area.

To summarize: There are in Class II areas about 8,500 wells annually discharging 869,000 acre-feet of water in the defined portion of the Southwest.

Further expansion of ground-water recovery in the six Class I ground-water areas does not appear to have great possibilities. Waters of the Arkansas Valley are almost completely developed. It has been estimated in the Kansas portion of the valley that it would be possible to develop by irrigation-wells approximately 40,000 acres of additional land with an estimated consumptive use of 70,000 acre-feet of water annually, without detrimental effects upon existing Kansas surface-water rights. No additional ground-water developments can be made in the Colorado portion of the basin because of existing water-adjudications.

In the Cimarron River Basin, the lands of the alluvial bottoms are little suited topographically to the spreading of water, nor are the soil-types conducive to economical irrigation. Along the course of the Cimarron River to the 99th Meridian, preliminary estimates indicate that probably

less than 17,000 acre-feet of water annually can be applied profitably to land suitable for irrigation. Because of the scattered character of these lands, irrigation will probably have to be effected by means of wells. Similarly, in the Canadian River Basin there is an abundance of readily recoverable ground-water in the alluvium but the lands are extremely sandy in character and rough topographically. Preliminary surveys indicate that probably less than 15,000 acres of land can be irrigated along the Canadian River with a probable annual consumptive use of ground-water amounting to approximately 26,000 acre-feet. West of the 99th Meridian the amount of irrigable land along the Red River and tributaries is probably less than 3,000 acres, and the estimated annual consumptive use would be approximately 6,000 acre-feet annually.

In the Pecos Valley about 29,000 acres are irrigated with water from the alluvium in New Mexico. It appears that little, if any, additional irrigation can be developed from unconfined alluvial waters in the New Mexico portion of the Basin. In the Texas portion of the Pecos River, near Barstow and Pecos, there is a possibility of developing some of the alluvial waters for well-irrigation. Here, however, as a result of constant upstream reuse of Pecos River water and for other reasons, future developments appear to be limited strictly to special soil-types. Current Department of Agriculture studies indicate that in the Texas portion of the Pecos River, probably less than 3,000 acre-feet of water per annum can be profitably applied.

The extent of present irrigation from surface-waters in the Rio Grande Basin together with current litigation, both domestic and international, over the use of these waters appear to preclude definitely the possibility of further pumping of ground-waters from the alluvium.

From the foregoing discussion of ground-waters along the channels of the major streams in the Southwest, it appears that in the valleys of the Pecos, and Arkansas of Colorado, and the Rio Grande there is little possibility of further development of ground-water without danger of costly litigation. Along the alluvial bottom lands of the remaining streams there is a possibility of using approximately 122,000 acre-feet of ground-water annually. This amount of ground-water development appears likely since the topography of the lands along these streams will probably prevent further surface-water developments, and the development of ground-water will not interfere with present surface-water appropriations.

Summarizing from the foregoing generalized data, the following conclusions may be drawn. In Class I ground-water areas, there is a possibility of developing additional ground-water, with an assured equivalent annual recharge, at a rate that probably will not exceed 122,000 acre-feet annually. In three of the major areas of Class II, namely, the Winter Garden Area, the San Luis Valley, and the Roswell Artesian Area, total feasible development probably has been reached, and additional development appears precluded for legal and economic reasons. In the Estancia Valley Area, a probable total of about 20,000 acre-feet can be developed. In the other two major areas, the Deming Area in New Mexico and the various districts on the High Plains, the rate of development is entirely dependent upon how quickly the water-table is lowered beyond the point of profitable pumping, for in these areas pumped water comes from partial storage.

Future development, with an assured annual recharge equal to the estimated potential annual recovery, appears to be limited to 122,000 acre-feet annually in Class I areas, plus 20,000 acre-feet annually in the Estancia (New Mexico) Area, or about 142,000 acre-feet. This total, plus the present recovery, indicates that the ultimate probable recovery rate will approximate 1,011,000 acre-feet annually. This figure includes the 560,000 acre-feet being pumped annually on the High Plains District and in the Deming Area, which come chiefly from storage. The lack of planning for those areas where ground-water can be exhausted constitutes a major irrigation and economic problem facing the Southwest.

It appears that the defined portion of the Southwest has arrived close to the end of another resource frontier. Just as a generation ago in the general West the seemingly inexhaustible frontier of new lands was reached, the Southwest is now approaching the frontier of ground-water resources. It has been assumed by many that, as our western irrigation economy expanded, with the perfection of pumping technique and with increasingly cheaper energy-rates, unlimited supplies of ground-water were awaiting development. Students of ground-water supply have observed the rapid approach of the last frontier of water and have recognized that the approach to this frontier is as inevitable as the close of the land-frontier in earlier years. The justifiable future development of ground-water is discouragingly small.

It is possible, of course, that crop-values may increase and thus permit pumping of water at heads considerably greater than those now deemed economic. If, however, future economic

conditions necessitate the abandonment of purely competitive well-irrigation developments, that is, if the investment in well-works and in other capital charges were to be assumed by other than the well-operator, water-users could pump from heads greater than those now considered practical.

It has been pointed out that major well-irrigation developments in the Southwest occur under conditions whereby the water-table will eventually decline below the point of profitable pumping. It is therefore important that, as quickly as feasible, research efforts in the field of hydrology be intensified. Too little is known of the precise effect that varying rates of recovery will have upon the rate of decline of the water-table. With a knowledge of the probable rates of lowering of the water-table, it is possible that more effective use of available water-supplies would be made. This type of research, of course, lies purely in the field of hydrology.

In the field of agricultural research, knowledge that will lead to a more effective ratio between application and the actual consumptive requirements of crops must be attained. To extract full value from the ground-water supply available, there must also be much research in the field of economics. Application of ground-water throughout the Southwest to crops that are not compatible with the general economy must be discouraged and the application of ground-water to crops most in harmony with the agricultural economy of the region must be encouraged.

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RECHARGE, MOVEMENT, AND DISCHARGE IN THE EDWARDS LIMESTONE RESERVOIR, TEXAS

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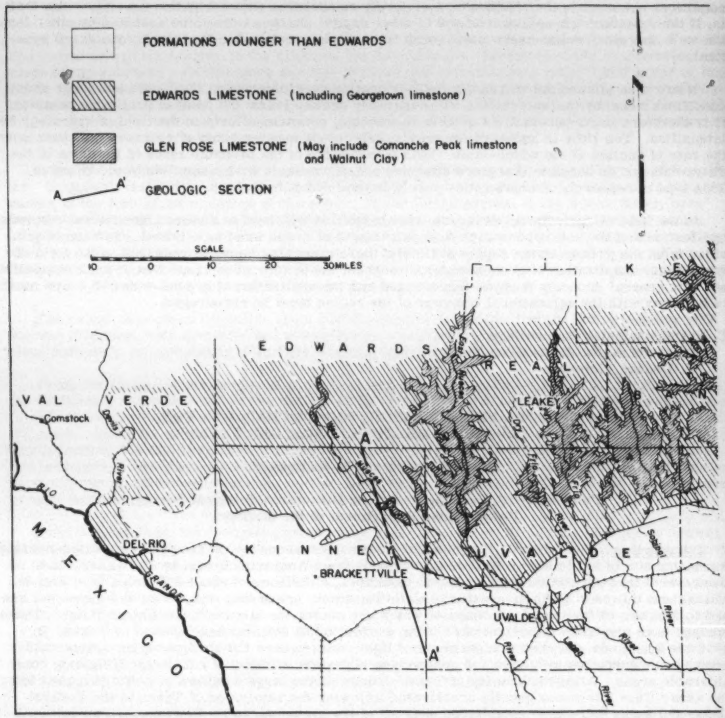
Introduction--The Edwards limestone of Lower Cretaceous age is the principal water-bearing formation in a belt 5 to 25 miles wide that extends from Austin southwest to San Antonio and thence west through Uvalde and Del Rio to Comstock, a distance of about 250 miles (see Fig. 1). Throughout this belt it supplies water to wells for stock, industrial, irrigation, and municipal use and to a series of fault-springs, some of which are among the largest in the United States. These springs have played an important part in the economic and cultural development of Texas. In 1718 the Spaniards stationed a department of light infantry near the springs at San Antonio and soon after established missions and constructed elaborate systems of canals for irrigating considerable areas. After the winning of Texas' independence large numbers of settlers moved into the area. This influx was greatly accelerated following the admission of Texas to the Federal Union and towns were soon established near all of the major springs. However, it was not until about 1880 that the rapid development of the Edwards limestone aquifer by wells was begun.

The belt of greatest productivity lies along the inner margin of the Coastal Plain where the Edwards is overlain by younger formations and the water is confined under artesian pressure. This belt nearly coincides with the Balcones Fault-Zone. The Edwards also yields water to wells and springs in its outcrop-area in the Edwards Plateau, which is the rugged country lying north of the Coastal Plain, but in the present discussion the principal importance of the Edwards Plateau lies in the fact that it is the recharge-area for the Edwards limestone artesian reservoir.

The evidence indicates that the hydrologic relations in the Edwards limestone reservoir are complex. Some of the water travels long distances underground. In view of the important part which the reservoir plays in the economy of the region and the fact that projects which affect the rate of recharge or discharge in one part of the belt may also affect the quantity of water discharged in another part, a thorough understanding of its hydrology is of primary importance.

The investigation of the Edwards limestone reservoir has been in progress more or less continuously for 12 years by the Federal Geological Survey in cooperation with the Texas State Board of Water Engineers. The investigation has included geological studies, inventories of wells, periodic measurements and continuous records of water-levels in wells, records of the discharge of wells and springs, and measurements of stream-flow. Several reports have been issued covering



various parts of the area [see 1, 2, 3, 4, 5, 6, 7, and 8 of "References" at end of paper] and a report on Kinney County is now in preparation.

Geology--The Edwards limestone is composed chiefly of massive bedded, crystalline to semicrystalline gray limestone. It ranges in thickness from about 350 feet at Austin to about 550 feet near Del Rio. It is underlain by the Comanche Peak and Glen Rose limestones which are generally rather impervious. It is overlain by the Georgetown limestone which between Austin and Uvalde is about 20 to 70 feet thick. Although the Georgetown is generally less permeable than the Edwards, Hill and Vaughan [9] considered it as the upper part of the Edwards limestone artesian reservoir rather than as an independent formation. West of Uvalde the Georgetown assumes the lithologic character of the Edwards and thickens to several hundred feet near Del Rio. In that part of Texas, Udden [10] has grouped the Edwards and the Georgetown limestones under the name Devils River limestone. In the canyon of the Devils River the Georgetown is the source of numerous large gravity-springs. In the area east of Devils River it may be the source of water in numerous wells but from Austin to western Kinney County the Edwards is believed to be the chief water-bearing formation. In this paper the term Edwards is retained for the artesian reservoir, although it is recognized that it may eventually be desirable to adopt the term Devils River artesian reservoir. The Georgetown limestone is overlain by the impermeable Del Rio clay which, except where it has been removed by erosion, acts as an upper confining bed for the artesian aquifer.

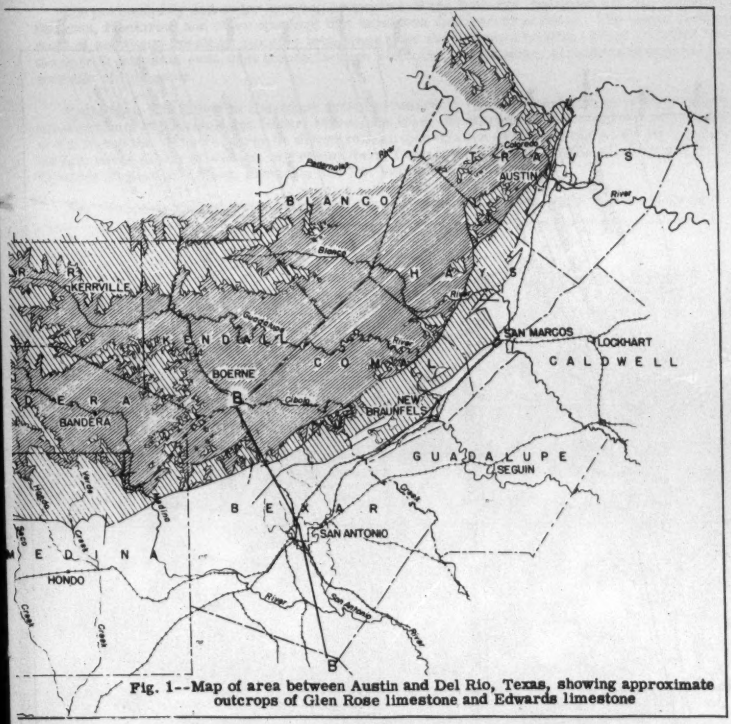
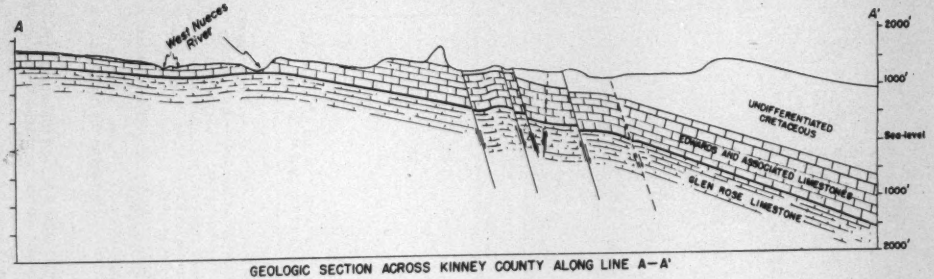


Fig. 1--Map of area between Austin and Del Rio, Texas, showing approximate outcrops of Glen Rose limestone and Edwards limestone

The Edwards and Georgetown limestones crop out in a continuous belt from Austin to beyond Comstock (see Fig. 1). From Austin to a few miles beyond New Braunfels the belt of outcrop is 5 to 15 miles wide and although deeply incised the formation is present both in the stream-valleys and on the hills. North of San Antonio the belt of outcrop is only three to four miles wide but the Edwards has been partly to completely eroded away in the stream-valleys. West of the Medina River the outcrop widens and the Edwards is at the surface in most of the Edwards Plateau. From the Medina River to the East Nueces River the Edwards is present in the beds of the streams from the southern margin of the plateau northward for a few miles, but farther north it has been removed from large areas in the stream-valleys exposing the Glen Rose. West of the East Nueces River the streams have generally not cut through the Edwards and the formation occupies the valleys throughout their length.

A few miles north of the southern edge of the Edwards Plateau the Edwards limestone dips gently to the south or southeast; but near the margin of the plateau the dip increases suddenly and at the Balcones escarpment the limestone passes beneath the younger formations of the Coastal Plain. Figure 2 shows two geologic sections approximately at right-angles to the strike in Bexar County and Kinney County. From Austin to the Medina River the Edwards is offset or nearly offset by faults at the Balcones escarpment. West of the Medina the throw of the faults becomes progressively less and in Kinney County the displacement of the formation is largely due to the increased dip.



GEOLOGIC SECTION ACROSS KINNEY COUNTY ALONG LINE A—A'

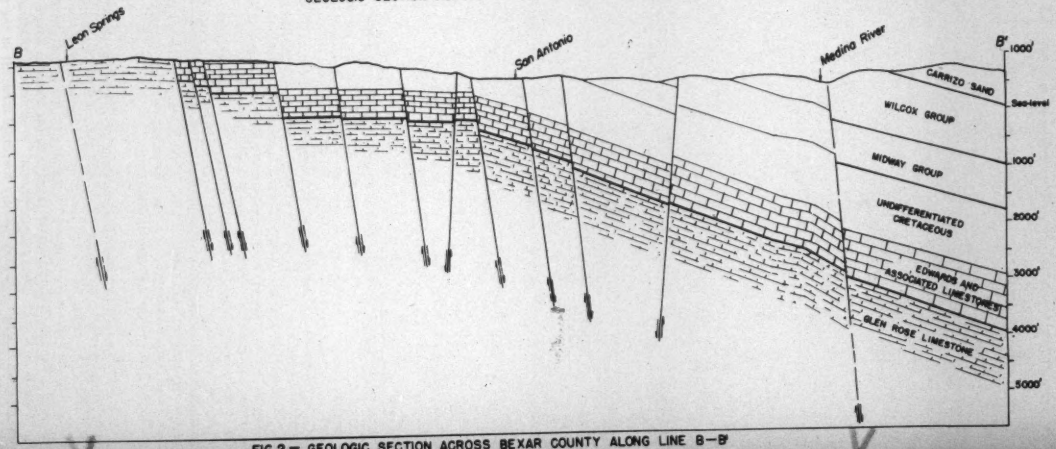


FIG. 2 — GEOLOGIC SECTION ACROSS BEXAR COUNTY ALONG LINE B—B'

The permeability and water-bearing properties of the Edwards limestone are due largely to fissures, fractures, and other openings that have been enlarged by solution. The major development of solutional openings probably took place after the Balcones faulting, which provided fissures with dominant east-west trends through which the ground-water circulated dissolving large amounts of limestone.

Recharge--The Edwards limestone artesian reservoir receives recharge in part by direct penetration of the rainfall and in part by seepage from the streams which cross the outcrop-area of the formation. The recharge by direct rainfall-penetration occurs chiefly along the southern margin of the Edwards Plateau in Travis, Hays, Comal, Medina, and Uvalde counties and in the Edwards Plateau in Kinney, Edwards, and Val Verde counties.

The recharge from streams occurs chiefly in Uvalde and Medina counties from a few miles

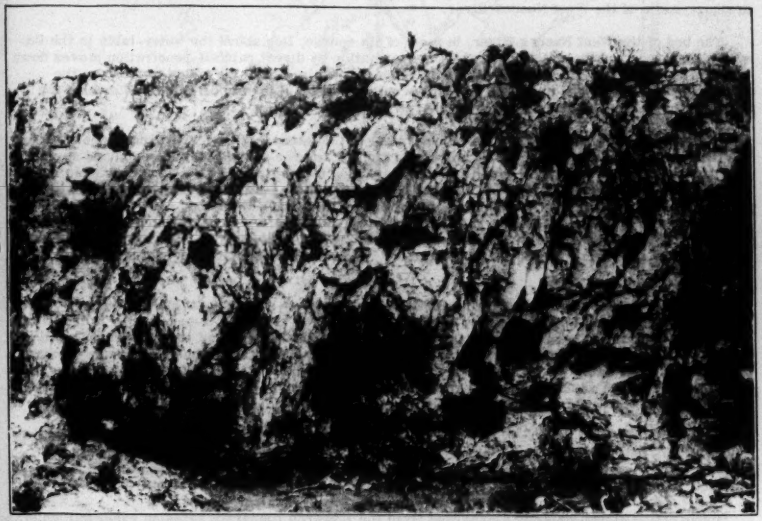


Fig. 3--Fractured Edwards limestone in the Balcones fault-zone, West Nueces River, Texas

north of the southern margin of the plateau to the Balcones escarpment. In this stretch, the streams, such as the East Nueces River, which in their upper reaches have a generally increasing flow, cross the outcrop of the Edwards and lose large quantities of water into the cavernous and fractured limestone (see Fig. 3). On the basis of discharge-records at gaging stations above and below the limestone outcrop in the river-bed and on the basis of seepage-investigations, the volume of water lost from the East Nueces River into the Edwards limestone is estimated to average about 34,000 acre-feet annually (one acre-foot equals 325,851 gallons). This water moves downward through the limestone and enters the Edwards limestone artesian reservoir. In a like manner, losses occur also on other streams as far east as the Medina River. It has been estimated that the combined losses to the Edwards limestone from the East Nueces, Dry Frio, Frio, Sabinal, and Medina rivers, and Hondo Creek (see Fig. 1) may average as much as 150,000 acre-feet a year [2, p. 77].

The West Nueces River in Kinney and Edwards counties and Cibolo Creek in northeastern Bexar County and many smaller streams do not generally have a flow, but during and immediately after heavy storms may contribute large amounts of water to the limestone reservoir. Other streams, such as the Devils River at the west end of the belt and the Guadalupe and Colorado

rivers in the eastern part of the belt, have cut down to the water-table and may receive water from the Edwards.

A comparison of precipitation-records with water-level fluctuations in wells that tap the Edwards Reservoir indicates that before any appreciable recharge occurs from rainfall the rains must be of sufficient intensity and quantity to cause the water to flow over the land-surface for at least short distances and thus reach solutional openings and fractures. Apparently, under most conditions, rainfalls must exceed one inch in 24 hours in order to cause appreciable recharge. Rainfalls of less than one inch in 24 hours are apparently dissipated by evaporation and transpiration.

The estimation of the amount of recharge that occurs by a direct penetration of rainfall throughout the outcrop-area is extremely difficult and has, so far, been attempted only in the drainage-basin of the West Nueces River.

The bed of the West Nueces River, in most of its course, lies above the water-table in the Edwards limestone and the water that enters the formation by direct rainfall-penetration moves down the dip and enters the Edwards limestone artesian reservoir. Since the water that enters the formation does not return to the surface in the outcrop-area, it is not possible to determine the amount of recharge by measuring the discharge of the stream.

However, in the East Nueces River Basin, most of the water that enters the limestone by direct rainfall-penetration in the drainage-basin above Laguna returns to the river in seeps and springs near the contact between the Edwards and the underlying formation. The discharge of these springs and seeps largely forms the sustained flow of the stream at the Laguna gaging-station and by analysis of the discharge-records, the amount of water that enters the limestone and returns to the stream above the measuring station may be estimated. The average ground-water runoff during the period of record--1923 to 1940--averages about 62,000 acre-feet a year, which is equivalent to an average annual rainfall-penetration of about 1.5 inches or about six per cent of the total annual rainfall.

It appears that the average rainfall-penetration in the basin of the West Nueces River in Kinney and Edwards counties is approximately equal per unit-area to the rainfall-penetration in the basin of the East Nueces River. Except during and immediately after periods of heavy storm-flow, there is no discharge at the mouth of the West Nueces. Since the total area of the West Nueces Drainage-Basin is about one-fourth larger than that of the East Nueces above Laguna, the total recharge from direct penetration of rainfall in the basin is probably considerably greater than the ground-water runoff in the East Nueces River above the Laguna gaging-station.

In northern Bexar County, with the exception of the area adjacent to Cibolo Creek, the Edwards limestone has been removed by erosion from most of the valleys and is offset by faulting at the southern margin of the plateau. Therefore, it is believed that no appreciable recharge to the limestone occurs in that part of the area.

Discharge--Ground-water is discharged from the Edwards limestone artesian reservoir chiefly by springs, but in some areas, notably near San Antonio, considerable amounts of water are discharged by wells. Figure 4 shows the location of the major springs. Most of the springs shown are artesian, the water rising along fissures through a considerable thickness of impermeable material. Goodenough, Comal, San Marcos, and Barton springs emerge near the edge of the Edwards Plateau and probably are gravity-springs largely localized by faults.

Table 1 shows the average discharge and in most cases the maximum and minimum discharge from these springs determined from measurements by the Federal Geological Survey and Texas Board of Water Engineers over a period of more than 40 years. According to these measurements, the combined average discharge of the major springs between Austin and Comstock and from the wells near San Antonio is 1,370 cubic feet a second or about 991,000 acre-feet a year. If the belt is divided into three parts according to the location of the springs and wells along the 250-mile stretch from Comstock to Austin the distances and the average annual discharges are as follows: Comstock to east boundary of Brackettville, 55 miles, 495,000 acre-feet; east boundary of Brackettville to Leon Creek west of San Antonio, 112 miles, 14,000 acre-feet; Leon Creek to Austin, 83 miles, 482,000 acre-feet. This illustrates the fact found early in the investigation that most of the discharge from the Edwards limestone reservoir is in the two end sections of the Comstock-Austin line, being about equal for the two sections, while the discharge in the middle section, the longest of the three, is comparatively small. On the other hand, a large part of the recharge to the reservoir occurs in the central and western sections.

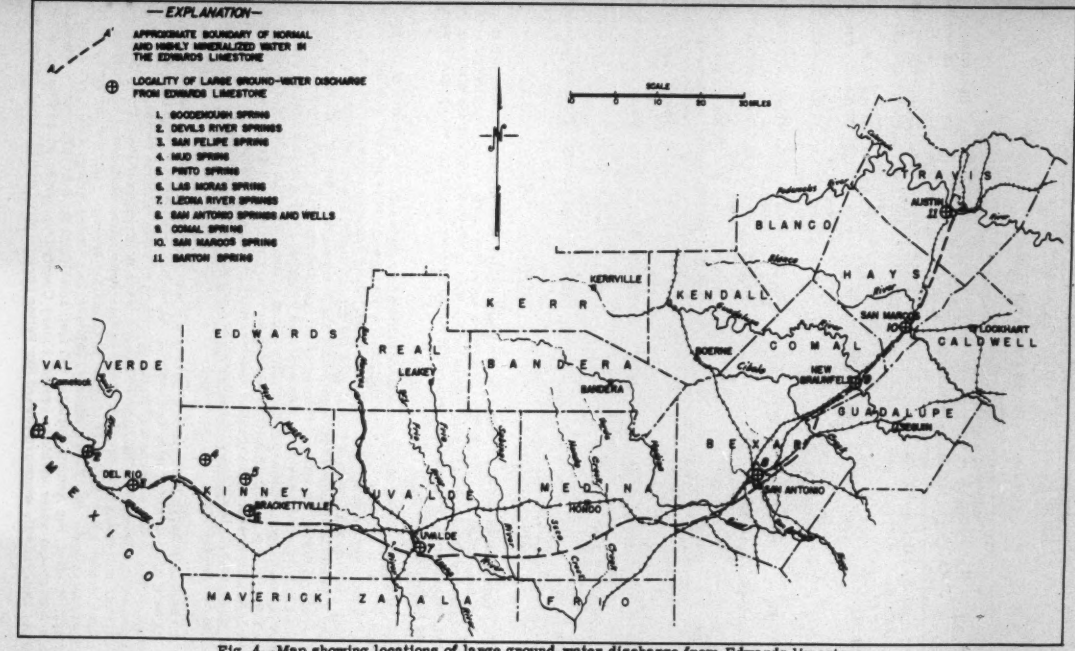


Fig. 4--Map showing locations of large ground-water discharge from Edwards limestone

Table 1--Major ground-water discharge from Edwards-Georgetown limestone between Austin and Comstock, Texas

(Springs are listed from west to east)

Spring or well	Cubic feet a second			Average annual discharge in acre-feet	Period of record	Remarks
	Average	Maximum	Minimum			
Goodenough Spring	160	---	93	115,834	1921 to 1939	Daily records
Devils River Springs	418	---	---	302,618	1901-1913, 1925-1930	Daily records
San Felipe Spring	76	150	41	55,021	1895-1931	55 measurements
Mud Spring	3	7-1/2	1	2,172	Feb. 1939 to Oct. 1940	17 measurements
Pinto Spring	6-1/2	9	4	4,778	Sept. 1939 to Oct. 1940	12 measurements
Las Moras Spring	21	60	6	15,203	1895 to Aug. 1940	36 measurements
Leona River Springs	18-1/2	27	12	13,393	June 1939 to Sept. 1941	Daily records
San Antonio						
Springs	55	---	---	39,818	1915 to 1935	Daily records of springs; discharge from wells partly estimated
Wells	110	---	---	79,636		
Comal Spring	315	380	246	227,560	Dec. 1927 to Aug. 1941	Daily records
San Marcos Spring	144	286	51	104,512	1894 to May 1941	132 measurements
Barton Spring	43	151	12	31,130	1894 to May 1941	351 measurements
Total average	1,370	---	---	991,471		

The wells, both flowing and non-flowing, in the Edwards limestone at San Antonio were estimated to yield an average of about 80,000 acre-feet a year. One well recently drilled into the Edwards limestone in San Antonio is reported to have a flow of about 17,500 gallons a minute, or about 25,000,000 gallons a day, which is believed to be the largest discharge from a single well in the United States.

Movement of water--In an homogeneous aquifer the water moves in the direction of the hydraulic gradient and at right-angles to the contours on the piezometric surface. Contours constructed on the piezometric surface of the Edwards limestone artesian reservoir in Kinney, Uvalde, Medina, Bexar, and a part of Comal counties are, in general, parallel to the strike of the limestone and it would be supposed that most of the water moves down the dip. However, there is no visible natural discharge south of the line of springs and the water in the limestone reservoir becomes highly mineralized or contains hydrogen sulphide. A line approximately demarking the boundary between the normal and highly mineralized ground-water is shown in Figure 4. The presence of this highly mineralized water indicates that the circulation of ground-water is slower and that the solutional openings are smaller and fewer in the limestone south of this line than north of it. Therefore, it is believed that little water moves southward through the limestone beyond this line of demarkation.

Inasmuch as the recharge in the central part of the belt greatly exceeds the visible discharge and there appears to be little opportunity for underground discharge down the dip beyond the line of the springs, it is concluded that considerable quantities of water must move through the aquifer nearly parallel to the strike of the formations and issue in springs far from the recharge-areas. That such movement may occur is shown by the comparative altitudes of the various springs. The altitudes above sea-level of some of the major springs, representing the approximate head, are as follows: San Felipe Springs, 950 feet; Las Moras Spring, 1,100 feet; Leona River Springs, 860 feet; San Antonio Springs, 670 feet; and Comal Springs, 625 feet. Evidently there is a major ground-water divide in central Kinney County from which water may move from the vicinity of Brackettville westward toward San Felipe Springs or eastward to San Antonio and

perhaps as far as New Braunfels.

The fact that the water in the Edwards artesian reservoir appears not to be moving perpendicular to the contours may be explained chiefly by the fact that the formation is not a homogeneous medium. It is fractured by east-west trending faults which, with their associated fracture-planes, provide ready channels for the movement of ground-water in the east-west direction and enlargement by solution has increased their water-carrying capacity. For this reason the ground-water moves more readily in the east-west direction than in the north-south direction.

The number of faults increases from Kinney County toward San Antonio. Thus, the opportunity for widespread development of solutional openings increases toward the east. Furthermore, the quantity of water moving through the openings increases by accretion from recharge and hence the amount of solution increases toward the east. The fact that in the Kinney County Area the wells are generally less productive and the water-levels fluctuate erratically, whereas in the San Antonio Area most wells have large yields and the water-levels fluctuate uniformly indicates that the development of solutional openings has been more widespread to the east.

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U. S. Geological Survey,
Washington, D. C.

SOLUTION-PHENOMENA IN THE PECOS BASIN IN NEW MEXICO

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(Published with the approval of the Director, Geological Survey,
United States Department of the Interior)

The drainage-basin of the Pecos River in New Mexico is a broad asymmetric trough extending from the Sangre de Cristo Mountains southward into Texas (see Fig. 1). It is bounded on the east by the westward facing escarpment of the High Plains and on the west by the crests of the Guadalupe, Sacramento and Sierra Blanca mountains, and a poorly defined divide extending northward through Gallinas Mountain and Pedernal Mountain to Glorieta Mesa. Most of the basin is formed by extensive upland erosion-surfaces that slope gently toward the river. The valley proper, through much of its length, is relatively narrow and is bounded by steep marginal bluffs, but in some sections, notably between Acme and Lakewood (the Roswell artesian basin) and between Carlsbad and Black River, it is considerably expanded and the lowlands adjoining the river extend from 3 to 16 miles back from the river.

The uppermost of the extensive erosion-surfaces in the Pecos Basin was called the Sacramento Plain by Nye [see 1 of "References" at end of paper, p. 14]. Remnants of this pediment are

preserved in the interstream areas in the Sacramento Mountains and it forms most of the broad western part of the basin north of the Capitan Mountains. The Sacramento Plain appears to have been coextensive with the High Plains [1, p. 97] and was formed in late Tertiary time by eastward flowing streams that antedated the Pecos River. Two lower pediments, the Diamond A Plain [1, p. 14] on the west side of the Pecos and the Mescalero pediment [2] on the east side, were formed

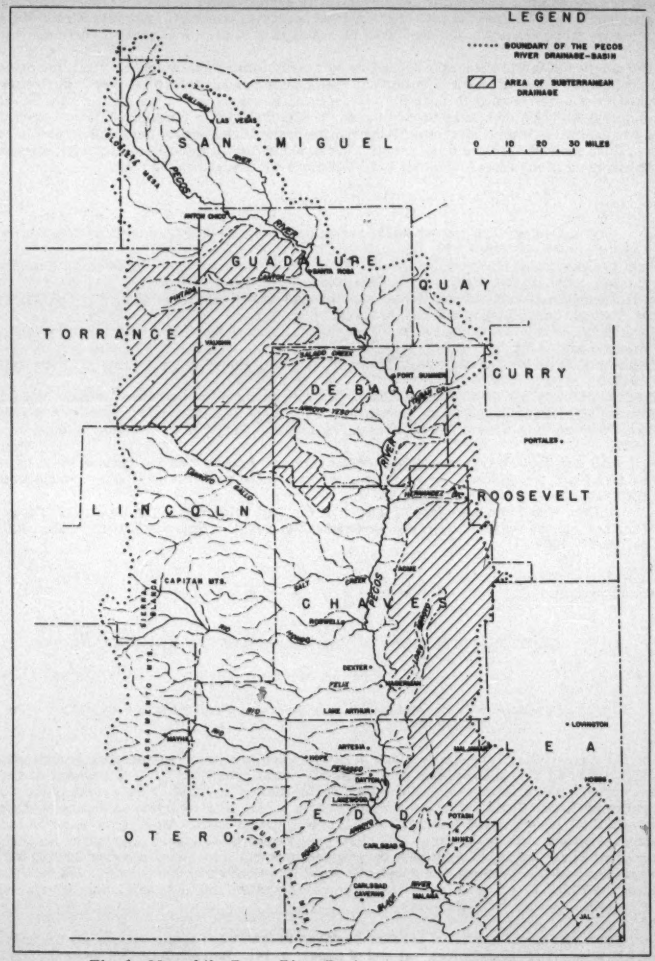

Fig. 1--Map of the Pecos River Drainage-Basin in New Mexico

by tributaries to the Pecos when it occupied a position 150 to 200 feet above its present channel. The Diamond A Plain is 400 to 1,300 feet below the level of the Sacramento Plain and is largely confined to the eastern part of the foothills of the Sacramento and Sierra Blanca mountains. The Mescalero pediment occupies most of the eastern part of the Pecos Basin. It heads against the escarpment of the High Plains and slopes westward toward the river. When projected westward the Mescalero pediment intersects the eastward projection of the Diamond A Plain a short distance west of the present channel of the Pecos. About 95 per cent of the excavation of the Pecos Basin was accomplished during the Diamond A - Mescalero cycle, which therefore appears to have occupied much of the Pleistocene.

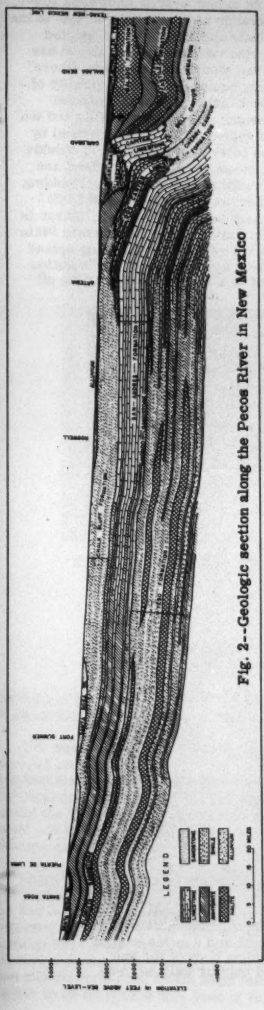

Fig. 2--Geologic section along the Pecos River in New Mexico

Solution has controlled to a large extend the position and efficacy of the surface-streams and has accomplished much of the actual excavation of the basin. Subterranean drainage through solution-channels has inhibited many of the streams and in some large areas it has completely disrupted the surface-drainage systems. In other sections depressions created by the collapse of the surficial rocks into solution-cavities have been contemporaneously filled by debris carried by the streams, thus contributing to the general lowering of the land-surface although the final result may superficially appear to be entirely the work of surface-streams.

The Pecos Basin south of Anton Chico is underlain by a thick section of Permian rocks made up largely of limestone, gypsum, and halite (see Fig. 2). Most of these rocks are exposed at the surface in the broad western part of the basin and in a narrow belt immediately east of the river. Throughout most of the area east of the Pecos they are overlain by Triassic redbeds and sandstones. The beds of halite that make up substantial proportions of many of the Permian formations do not crop out at the surface but they are exposed to solution by water circulating through aquifers with which they are interbedded or otherwise in contact.

Although solution-phenomena are associated with nearly all of the Permian formations in the Pecos Basin, those exercising the most pronounced effects on the geomorphology of the area are associated with the San Andres and Salado formations. The characteristics of these formations will therefore be considered in some detail.

Solution-phenomena associated with the San Andres formation--The San Andres formation is the most extensively exposed of all the formations in the Pecos Drainage-Basin. It crops out in the uplands in the western part of the basin in a belt 25 to 60 miles wide that extends from the north end of the Guadalupe Mountains to Glorieta Mesa. It has a regional southeastward dip of about 50 feet to the mile which carries it beneath younger beds 12 to 30 miles west of the Pecos River, and it underlies the river at depths ranging from a few hundred feet, at Santa Rosa, to about 1,300 feet at Lakewood. In the area south of the Capitan Mountains the San Andres is made up almost entirely of limestone but to the north many of the beds grade into anhydrite, and in the vicinity of Vaughn the formation consists largely of gypsum and gypsiferous limestone. East of the Pecos River, northeast of Roswell, beds of halite appear in the formation, and near Fort

Sumner halite makes up about 30 per cent of its total thickness. The formation is 1,000 to 1,200 feet thick in the Sacramento Mountains and the Roswell artesian basin but to the north it thins to about 700 feet near Vaughn and Santa Rosa.

The San Andres is extremely cavernous throughout most of its extent west of the Pecos River, and subterranean drainage is important throughout this area. Solution of the limestone beds in the formation has resulted in "honey-combed" and "worm-eaten" beds and small interconnected pipes and tubes rather than large open caverns. Sink-holes and other evidences of collapse are therefore not common in the limestone areas. North of the Capitan Mountains, however, where the formation is largely composed of gypsum, sink-holes are very numerous. In the vicinity of Vaughn the Sacramento Plain is scarred by innumerable small sink-holes, 20 feet to several hundred yards in diameter, and a number of large closed depressions several miles wide and ten miles or more long (see Figs. 3 and 4). The larger depressions appear to have been formed by the integration of many small sink-holes that developed along the outcrop of particularly soluble beds. The floors of many of the depressions are 200 to 300 feet below the adjoining upland and are underlain by as much as 180 feet of alluvium which has been washed in from the surrounding areas. Between Arroyo Gallo and Pintada Canyon (see Fig. 1) there is an area of about 2,000 square miles that is drained entirely through subterranean channels in the San Andres. There is no evidence of through drainage across this section since the completion of the Sacramento Plain in the late Tertiary. The moderate dissection of the area which has resulted in a rolling upland surface with relief of about 300 feet has been accomplished entirely by the process of "solution and fill" as described by Lee [3]. If the area were again reduced to a level plain by cutting off

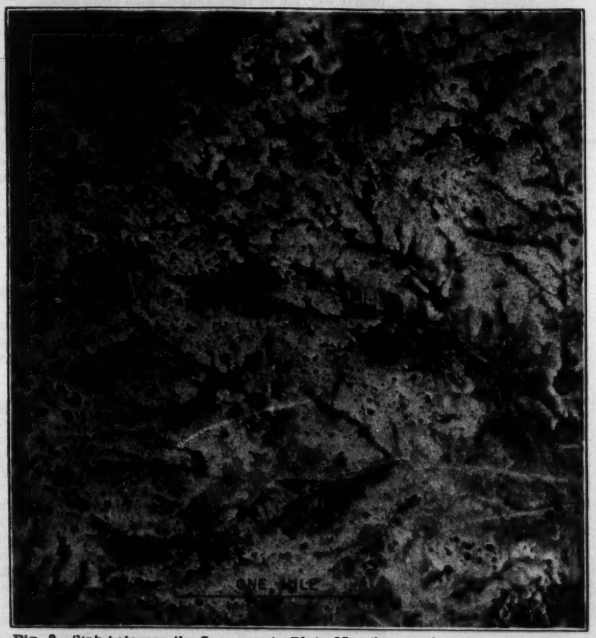

Fig. 3--Sink-holes on the Sacramento Plain 25 miles south and 6 miles east of Vaughn, New Mexico; gypsum and gypsiferous limestone beds of the San Andres formation exposed at the surface or mantled only by caliche; note the incipient integration of drainage-lines

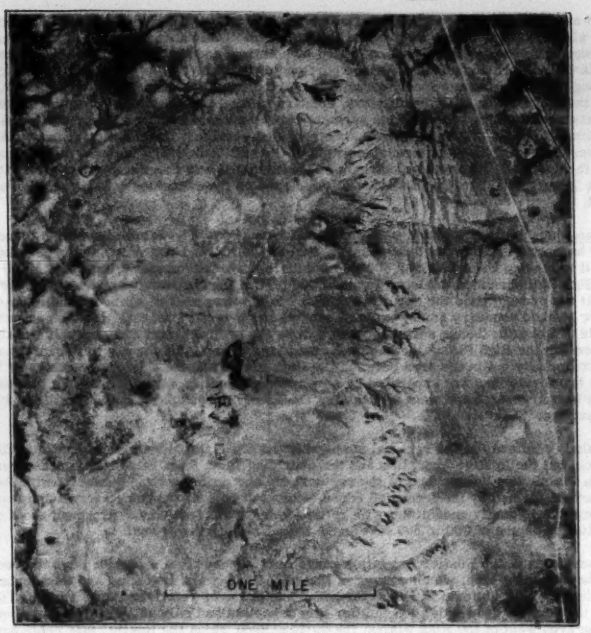

Fig. 4--Eastern part of a large sink-depression (left) and relatively undisturbed Sacramento plain (right) 25 miles south and 16 miles east of Vaughn, New Mexico; the ranch buildings (left center) are about 250 feet below the level of the plain and a well near the buildings penetrated 180 feet of alluvium; the gypsum and gypsiferous limestone beds of the San Andres formation are covered here by an unknown thickness of silt and shale belonging to the Chalk Bluff formation (Permain) and the Ogallala formation (Tertiary)

the tops of the ridges to fill the depressions, there would be a general lowering of the land-surface of about 100 feet.

The water absorbed by the San Andres in its outcrop-areas migrates down dip and is discharged into the Pecos River through springs near Santa Rosa and in the Roswell artesian basin. Seepage from the river where it crosses the San Andres outcrop near Collonias and water from the outcrop-area north of Vaughn return to the surface in the springs near Santa Rosa. Water entering the formation at its outcrops on the east flank of the Sacramento Mountains and in the uplands north of the Capitan Mountains, possibly from as far north as Vaughn, returns to the surface through springs and wells in the vicinity of Roswell.

Much of the water that is discharged from the San Andres formation in the northern part of the Roswell Basin is strongly impregnated with sodium chloride. Beds of halite are present in the San Andres formation in the area east of the Pecos River north of Acme, but none has been reported in or east of the Roswell artesian basin. Apparently some of the water moving from the outcrop-area near Vaughn to the Roswell artesian basin follows an arcuate path that brings it into contact with the beds of halite north of Acme. The halite members of both the San Andres formation and the overlying Chalk Bluff formation are abruptly cut off near the Pecos River. There seems to be no reason why beds of halite which east of the Pecos are distributed through a

2,000-foot sequence composed largely of anhydrite, limestone, and redbeds should not have been deposited also in this sequence west of the Pecos River. Their absence, west of the river, strongly suggests that they have been removed by solution, and that their present western limit represents the eastern boundaries of those portions of the San Andres and Chalk Bluff formations through which water can freely circulate. Furthermore, the ancestral Pecos River, as shown by the distribution of its headwaters, appears to have been established on the eastward-sloping Sacramento Plain--High Plains surface, but the present course of the river south of Fort Sumner forms an angle of about 70° to the slope of that surface. The position of the modern Pecos River at or near the western extremities of the salt beds with a trend at almost right-angles to the course of its ancestral stream suggests that it was fixed in approximately that position by the integration of trains of sinks that developed on the Sacramento Plain through solution of the salt.

Solution-phenomena associated with the Salado formation--The Salado formation is composed largely of halite with some interbedded anhydrite, polyhalite, and red sandy shale. Southeast of Carlsbad it reaches a thickness of 2,400 feet but farther north it ranges from about 1,300 feet near the High Plains east of Carlsbad to about 300 feet in the southeastern part of Roosevelt County. At the present time the Salado is confined to the area east of a line extending from the Texas-New Mexico boundary northwestward beneath the river to Carlsbad, thence northward to the latitude of Roswell, thence northeastward across the southern part of Roosevelt County into Texas. Beneath the High Plains the Salado formation is overlain by the Rustler formation with apparent conformity but in the area between the High Plains and the western boundary of the Salado the two formations are separated by a pronounced angular unconformity. In this area the Salado has been truncated and west of this area the Rustler overlaps upon the Castile and Chalk Bluff formations.

The Salado conforms to the regional southeastward dip of the older formations in Southeastern New Mexico, but the Rustler formation and the overlying Santa Rosa sandstone, in the area west of the High Plains, are independent of the regional dip and conform almost exactly with the irregular surface formed by the truncated edges of the salt beds of the Salado formation (see Fig. 5). This surface is gently undulating, with relief of 200 to 300 feet, and, throughout most of its extent, it lies at depths of 200 to 500 feet below the surface of the ground.

The basal beds of the Rustler formation range in thickness from a feather edge to about 60 feet, but the overlying beds, which consist of thin beds of clay and fine sand and thick massive beds of anhydrite, are uniform in character and thickness over relatively large areas. This indicates that the surface upon which the Rustler was deposited had only about 60 feet of relief. However, in the area west of the High Plains, the surface upon which the Rustler now rests has relief of over three times that amount and, disregarding its undulations, it is essentially flat lying whereas beneath the High Plains it has a regional southeastward dip of about 50 feet to the mile. The structure of the underlying Salado formation shows that the undulations of the top of the salt and the abrupt break in the regional slope of that surface near the escarpment of the High Plains are not due to diastrophism. Therefore, the irregularities in the top of the salt and the distortion of the overlying beds must have been induced by removal of salt from the Salado after the Rustler formation and the Santa Rosa sandstone were deposited. The only way in which the salt could be removed from beneath the Rustler formation is by solution of the salt by ground-water circulating through the basal beds of the Rustler in contact with the upper surface of the salt. Many wells in the area east of the river have encountered water in the base of the Rustler formation, and near Malaga, southeast of Carlsbad, brine from this aquifer, carrying about 350 tons of salt per day, is being discharged into the river.

It is evident from the east-west cross-section through Artesia (see Fig. 5) that, in order to restore the surface upon which the Rustler formation was deposited to an essentially flat plane without disturbing the very uniform regional dip of the underlying beds, the Salado formation would have to be projected some distance west of its present boundary with only a gradual decrease in thickness. It therefore appears reasonable to assume that it formerly extended at least a short distance west of the Pecos River. Figure 6 shows the geologic section through Artesia as restored to its condition at the end of the Tertiary. In the restoration the Salado has been projected about 17 miles west of its present boundary, and, since it would have been exposed to solution during the cutting of the Sacramento Plain, it has been truncated in a manner similar to that shown in the present cross-section.

During the long period of erosion that resulted in the development of the Sacramento Plain - High Plains surface, the depressions created by solution of the salt were probably filled with

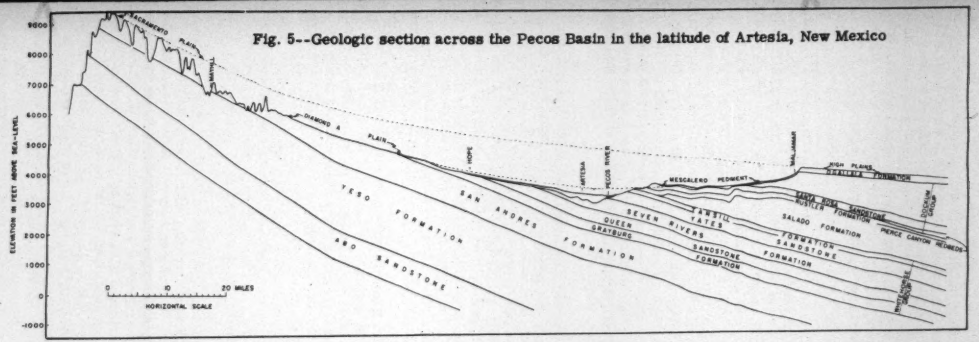

Fig. 5--Geologic section across the Pecos Basin in the latitude of Artesia, New Mexico

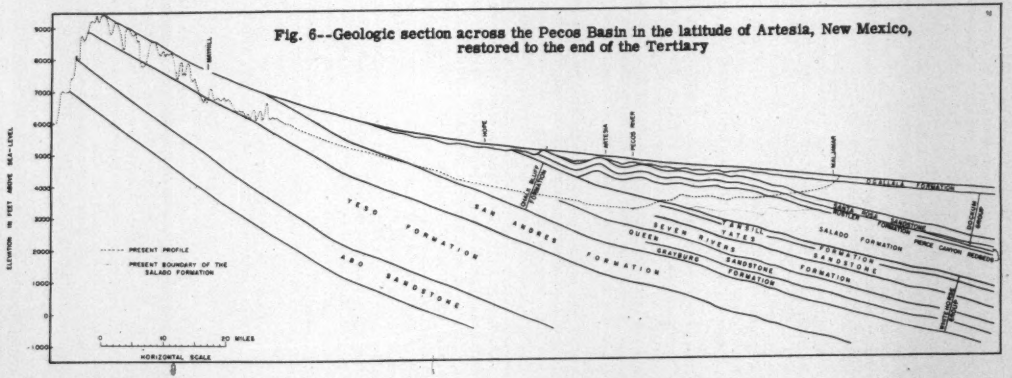

Fig. 6--Geologic section across the Pecos Basin in the latitude of Artesia, New Mexico, restored to the end of the Tertiary

debris carried by the eastward flowing streams with only temporary disruption of the stream-courses. Solution would be most active along the western extremity of the salt, where it was most exposed to fresh water. Consequently the sinks were probably most numerous in a zone near the boundary of the salt that roughly paralleled the present course of the river. A short distance north of Roswell the train of sinks overlying the western extremity of the Salado would intersect the north-south train of sinks created by the removal of salt from the San Andres formation in the area between Fort Sumner and Acme, thus forming a more or less continuous suballuvial depression filled with loosely consolidated sand, gravel, and clay that extended from Fort Sumner southward into Texas. Eventually this depression was tapped by a tributary of the Rio Grande, which by headward erosion captured successive eastward flowing streams and established the present Pecos River Drainage-System.

After the establishment of the Pecos River the excavation of the basin proceeded rapidly, and toward the latter part of the Pleistocene the river, in the latitude of Artesia, occupied a position about 1,300 feet below the Sacramento Plain-High Plains and was flanked by extensive pediments--the Diamond A Plain on the west and the Mescalero pediment on the east. Although both pediments superficially appear to be the result of long-continued stream-erosion, much of the actual excavation of the basin, particularly east of the river, has been accomplished by solution. In Figure 6 the interval between the hypothetical position of the top of the Salado at the end of the Tertiary and the present top of salt as shown by the dotted line represents the volume of material removed from the Salado formation alone, practically all of which was removed prior to the end of Mescalero time. The space occupied by the removed salt is about 40 miles wide and about 800 feet thick at the thickest part and has a cross-sectional area equivalent to a rectangle 40 miles wide and about 500 feet thick. In the latitude of Artesia the volume of salt removed from beneath the area east of the river amounts to about 56 per cent of all the material removed from that area between the end of the Tertiary and the end of Mescalero time.

Since the end of Mescalero time the river has cut down an additional 150 to 200 feet and two intermediate pediments have been carved out of the alluvium underlying the lowlands west of the river in the vicinity of Roswell and in the area south of Carlsbad. East of the river there are no correlatives of the intermediate pediments and the Mescalero pediment has suffered only a relatively small amount of dissection, most of which can be attributed directly to solution of the rocks underlying it. Only a few streams cross the pediment south of Fort Sumner and they drain only small areas immediately adjoining their channels. The remainder of the area east of the river has interior or subterranean drainage (see Fig. 1). The pediment is scarred by large sink-depressions, some of which form trains parallel to the strike of the underlying Salado formation. Long Arroyo, which intersects the Pecos River near Hagerman and is one of the few arroyos that extend more than a few miles east of the river, appears to have been formed by the integration of one of these trains of sinks. Through most of its length it overlies the present boundary of the Salado formation and its trend is approximately at right-angles to the slope of the Mescalero pediment. Another prominent train of sinks extends from a point a few miles northwest of Maljamar southward through the Potash Mines area and intersects the Pecos River near Loving. This series of depressions was once integrated into a continuous trough and had through drainage to the river but continued subsidence along the axis of the trough has completely disrupted the channel and has broken it into a number of discrete basins each of which now has its own drainage-system. Although such streams as Long Arroyo and the one that formerly extended from Maljamar to Loving carried some debris out of the area, most of the products of stream-erosion were deposited in sink-depressions within a few miles of their point of origin.

Little if any of the water absorbed by the rocks underlying the Pecos Basin is carried out of the basin through subterranean channels. Most of the water, carrying with it the products of solution, is eventually discharged into the Pecos River. The concentration of the river-water increases downstream, with pronounced changes in the character and concentration taking place in the areas of known spring flow. The weighted average analyses of the river-water [4] for the year ending September 30, 1940, show, in parts per million of dissolved solids, concentrations of 131 at Anton Chico, 1,642 at Puerta de Luna, 2,910 at Artesia, 3,440 at the headgate of the Carlsbad Project Canal near Carlsbad, 4,030 at Malaga, and 5,120 at the Red Bluff gaging-station near the State line. In the three-year period ending September 30,1940, the load of dissolved solids annually discharged into the Pecos River in New Mexico, exclusive of that picked up in the Carlsbad Irrigation Project, averaged about 1,000,000 tons, or about 48 tons per square mile of the Pecos Drainage-Basin in the State. About 77 per cent of the total pickup of dissolved solids (783,000 tons) reached the river above Artesia and was contributed largely by ground-water discharged from the San Andres formation. The remaining 23 per cent (228,000 tons) was picked up between Malaga, at the lower end of the Carlsbad Project, and the Red Bluff gaging-station, and

was largely derived from the Salado formation. The load of dissolved solids carried by the river at Artesia is made up largely of sodium chloride (34 per cent or 266,000 tons) and calcium sulphate (42 per cent or 328,000 tons). Sodium chloride makes up about 73 per cent (165,000 tons) of the increase between the Malaga and Red Bluff stations and calcium sulphate makes up only 13 per cent (28,545 tons).

The volume of dissolved solids annually picked up by the river amounts to 298 acre-feet of which 224 acre-feet reaches the river above Artesia and 74 acre-feet is picked up between Malaga and Red Bluff. The volume of sodium chloride picked up between Malaga and Red Bluff is about 50 acre-feet. At the present rate at which sodium chloride is being discharged from aquifers in contact with the Salado formation, the volume of salt removed from the formation in 1,000,000 years would amount to 56 feet over an area of about 1,500 square miles, which is approximately the area now occupied by the truncated portion of the formation. This quantity is only about one-tenth of the quantity that has apparently been removed by ground-water since the completion of the Sacramento Plain. Water is taken into the aquifers in contact with the Salado largely at the outcrop of the basal beds of the Rustler formation, which at present forms a narrow belt lying 2 to 15 miles east of the river between Carlsbad and Roswell. During much of the time that the Pecos Drainage-Basin was being excavated the Rustler formation cropped out west of the river and probably received recharge from the streams flowing eastward from the mountains. During the latter part of the Mescalero-Diamond A cycle, when the Rustler had been removed from the area west of the river, its outcrop was crossed by streams flowing westward toward the river and probably received some recharge from these streams. Since the end of the Mescalero cycle all the westward flowing streams have been disrupted and the Rustler outcrop at present is crossed only by Long Arroyo. Consequently recharge to the Rustler at present is contributed only by rainfall-penetration in the narrow belt of outcrop and is probably considerably less than the quantities received in earlier periods when seepage from the streams was available to the formation. Under normal conditions, recharge to an aquifer is balanced by discharge of an equivalent amount of water. It is probable, therefore, that the quantity of brine discharged from the aquifers in the base of the Rustler formation prior to the end of the Mescalero cycle was considerably larger than that discharged at present.

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DEEP-SEATED SOLUTION IN THE MEADE BASIN AND VICINITY, KANSAS AND OKLAHOMA

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(Published by permission of the Director of the Geological Survey, United States Department of the Interior, the Director of the Kansas Geological Survey, and the Director of the Oklahoma Geological Survey)

Introduction

During the closing years of the 19th century, Haworth [see 1 and 2 of "References" at end of paper] and Johnson [3] noted the abundant depressions resembling sink-holes in the Southern High Plains, especially in Meade and Clark counties, Kansas, and Beaver County, Oklahoma. Johnson was of the opinion that all the depressions and basins in this region were due to solution, whereas Haworth [1] believed the Meade artesian basin to be structural, although he held to a solutional origin for the Ashland and Englewood basins, which are a few miles to the east.

During the field-seasons of 1939, 1940, and 1941 the authors had opportunity to study these

features in the field in connection with ground-water studies. The work in Kansas was a cooperative ground-water investigation by Frye under the sponsorship of the United States Geological Survey and the Kansas Geological Survey, with the cooperation of the Division of Sanitation of the Kansas State Board of Health, and the Division of Water Resources of the Kansas State Board of Agriculture, and was under the supervision of S. W. Lohman of the Federal Geological Survey. The work in Oklahoma was a cooperative ground-water investigation by Schoff under the sponsorship of the Federal Geological Survey and the Oklahoma Geological Survey.

The authors wish to express their thanks to H. T. U. Smith, C. W. Hibbard, S. W. Lohman, R. C. Moore, and Robert H. Dott for the helpful advice and criticism they have given during the course of this work. The manuscript of this paper was read and criticized by the last three named, and by O. E. Meinzer, Geologist-in-Charge of the Division of Ground Water of the United States Geological Survey.

Recent studies [4, 5, 6, 7] have indicated that the Meade artesian basin is partly structural in origin, but that many nearly filled depressions to the east of the basin appear to be due wholly to solution and subsidence. Although the present paper deals primarily with the origin of the sinks, it will be necessary to discuss briefly the structure and stratigraphy of the deposits in which the sinks have developed [6, 7].

The entire region is underlain by Permian redbeds. Locally, as shown by outcrops in the east and by test-holes farther west, Cretaceous rocks overlie the Permian. The Laverne formation, of early Pliocene age, crops out at many places, and although in general its basal contact is poorly exposed, the formation appears to overlie the Permian directly. Test-holes in the western part of the region indicate, however, that in places the Laverne overlies the Cretaceous. The Laverne has been folded somewhat, and the axis of an anticline in it is shown in Figure 1. After early Pliocene time, the Laverne beds were truncated by erosion, and during the middle Pliocene they were covered by terrestrial deposits comprising the lower part of the Ogallala formation. At the close of middle Pliocene time, the first movement occurred along the Crooked Creek and Fowler faults (Fig. 1) displacing Permian and Pliocene beds and thus giving rise to a basin, here termed the ancestral Meade Basin, in which were trapped the upper Pliocene deposits that constitute the Rexroad member of the Ogallala.

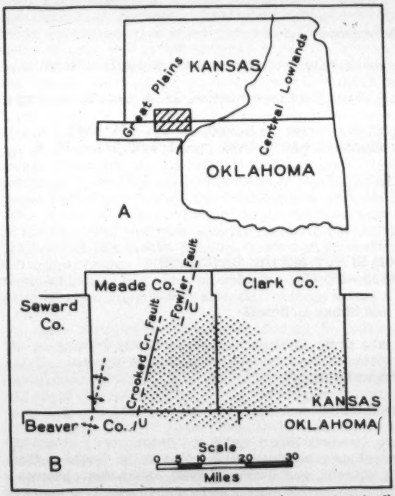

Fig. 1--A, index-map, showing area (cross-hatched) covered; B, map of Meade and Clark counties, Kansas, showing axis of a Pliocene anticline, Crooked Creek and Fowler faults, and area (stippled) where sinks occur

The development of the first of the sinks discussed here did not begin until after the close of middle Pliocene time, as indicated by the fact that wherever the rim rock of a sink is well exposed, the middle Pliocene deposits extend across the rim with no apparent thickening or thinning and are involved in the collapse. Furthermore, the oldest of the sink-hole fillings are Pleistocene in age.

Surface-features

The sinks differ considerably in surface-expression. Some of them are almost completely filled with Pleistocene and Recent deposits and others are only partly filled. In some, the filling has been deeply dissected, whereas others are as yet untapped by surface-drainage and still are receiving deposits. The undissected sinks appear as shallow surface-depressions, some of which contain ponded water during part of the year.

The sinks may be classified as follows:

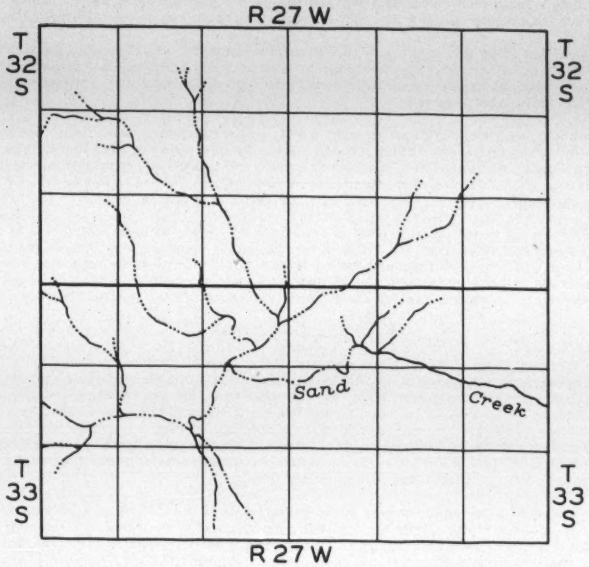

Fig. 2--Drainage-map of the "Jones Sink," showing centripetal drainage-pattern

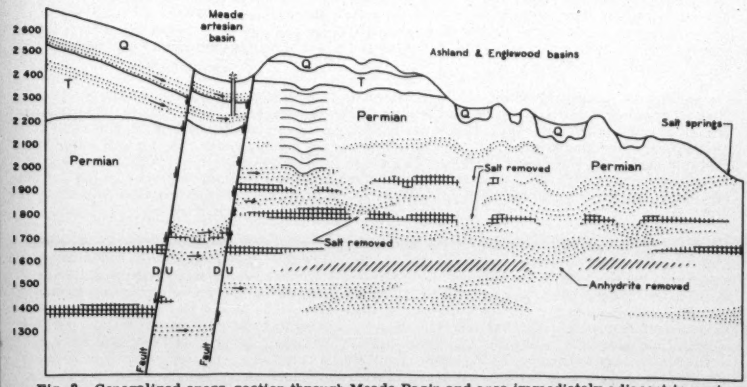

Fig. 3--Generalized cross-section through Meade Basin and area immediately adjacent to east showing supposed course of circulating ground-water

(1) Simple sinks that have undergone only one period of subsidence, and therefore contain deposits that are conformable but dip from all sides toward the central part of the basin.

(2) Complex sinks that have undergone several subsidences. In these, the later subsidences generally did not affect the entire area, but only parts of it. First one part of the floor collapsed and then another, and so gave rise to many diverse dips and local unconformities within the sediments that were being deposited.

(3) Coalescing sinks developed in large basins where sinks formed so close together that with further subsidence part of the rims between them collapsed, or were readily worn down by erosion. The basins so formed are irregular in outline and contain low curving ridges and knobs that mark the sites of the former rims. The Ashland and Englewood basins in Clark County, Kansas, and Beaver County, Oklahoma, are examples of this type of sink.

Surface-runoff resulting from rainfall ordinarily will enter an undissected sink by flowing down its sides from all directions. When a stream that is extending itself headward captures a sink, gulleys will appear in the sink, leading from all directions into the capturing stream. As the gulleys are cut deeper into the sink-filling and become distinct valleys, a centripetal drainage-pattern will be formed, as illustrated by the Jones Sink in east-central Meade County (Fig. 2).

Origin of the sinks

The fact that Permian redbeds are exposed in the rims of many of the sinks indicates that the post-Permian deposits, which generally contain only small amounts of soluble material, were relatively thin before subsidence began. On the other hand, the several thousand feet of Permian strata underlying the area include many soluble beds of salt and anhydrite. The logs of oil-wells and test-holes in the area reveal considerable thicknesses of these materials interbedded with each other and with shale, siltstone, and fine-grained sandstone, at depths ranging from 500 feet to more than 1,000 feet below the surface. Doubtless these were the rocks that were partly dissolved with resulting collapse and formation of sinks.

The sinks are on the upthrow side of the major faults of the area (Fig. 1), but down the dip of the beds from those faults. They are also down the gradient of the surface-streams from the faults and from the Meade artesian basin. As the initial fault-movement occurred during late Pliocene time, and the sinks were developed in latest Pliocene (?) and Pleistocene time, a causal relationship between the faults and the sinks is suggested. The ancestral Meade artesian basin adjoined the faults to the west, and so fresh water under hydrostatic pressure probably has had access to the fault-zones where Pliocene sediments are faulted against Permian redbeds, since late Pliocene time unless the faults are sealed tight by debris. This water could have moved down the faults to the soluble beds in the Permian, and thence eastward to points of lower elevation where it could emerge as salt springs and seeps along the outcrops of the Permian rocks (Fig. 3).

Morgan [8] has described solution-subsidence by deep-seated circulation in the Roswell Area, New Mexico, and has pointed out [letter to Frye, November 14, 1941] that in the beginning phases of solution the water must follow preexistent openings provided by bedding planes, joint cracks, and other fractures and planes of weakness in the soluble rocks, but that salt under load probably cannot maintain such openings. Thick beds of salt, therefore, are probably immune to solution at depth except along contacts with other rocks through which water can circulate. Thus they might become deeply channeled along contacts but would lack solution-cavities in the interior of the mass.

In the absence of open channels in the salt, through circulation of water within the Permian under the Meade Area would be restricted to the layers of fine-grained sandstone and possibly anhydrite. As the beds in the Permian generally are lenticular, water migrating through them would necessarily follow a somewhat indirect route, and here and there would come in contact with the top or bottom of a salt-bed, dissolving some of the salt. Where the water had access to salt under only a small area, the overlying shales probably had sufficient strength to support for a short time the roof of a cavern, which subsequently collapsed and produced a sink at the surface. Such seems to have been the history of the Meade Salt Sink, which, as reported by Johnson [3], suddenly appeared athwart a well-traveled trail near Meade in 1879. The water in this sink was at first salty but it gradually became fresh. Where the salt was dissolved from under a large area, however, the subsidence probably more nearly kept pace with the solution, and so the affected area gradually sagged to form a basin without a sharp break around the rim. A partly

dissected sink in Beaver County, Oklahoma, just south of the Kansas State Line, is thought to have originated in this way.

It is immaterial to the present hypothesis whether anhydrite supports open solution-channels at depth similar to those in limestone, or whether the openings are immediately sealed, as in salt. If open channels are maintained in it, the channels could act as passageways for circulating ground-water, could be enlarged in the same way as channels in limestone, and would be subject to collapse with the formation of sink-holes and karst topography. On the other hand, if channels can not exist in anhydrite, it could have been dissolved only where it was in contact with permeable water-bearing beds, such as sandstone, in the Permian.

Conclusions

In conclusion, it appears that sink-holes in and adjacent to the Meade artesian basin have resulted from the solution of salt and anhydrite at depths of 500 to 1,000 feet or more below the surface by deep-seated circulation of water from the artesian basin. This circulation was made possible by the late Pliocene faults that gave rise to the basin, and the sinks, therefore, are chiefly Pleistocene and Recent in age.

It is evident that some of the other depressions that are widely distributed over the Southern High Plains may have similar relationships to faults and bodies of either artesian water or unconfined water, but that part of them may have resulted from the removal of soluble beds within the Tertiary in places where the Tertiary deposits are thick [9, 10]. The origin here suggested for the depressions east of the Meade Basin, therefore, can not be applied to other depressions in the High Plains without careful examination of the geologic relationships.

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RESULTS OF PUMPING TESTS OF THE CARRIZO SAND IN THE LUFKIN AREA, TEXAS

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(Published with the approval of the Director, Geological Survey, United States Department of the Interior)

Introduction--The Lufkin Area, as the term is used in this paper, is comprised of Angelina and Nacogdoches counties, Texas, and parts of adjoining counties. Its surface is gently rolling, with a maximum relief of about 150 feet and a maximum altitude of less than 400 feet. The average annual rainfall is about 45 inches. Practically all of the water-supplies in the area come from ground-water and it has been found that the Carrizo sand contains water of better quality and is more productive than any other water-bearing formation in the area [see 1 of "References" at end of paper]. Figure 1 is a map of the area, showing the positions of the cities of Lufkin and Nacogdoches, the wells of the Southland Paper Mill, and other wells mentioned in this paper.

Geology--The Carrizo sand is a loosely-cemented moderately coarse-grained sand, with thin shale lenses, lying unconformably on the Wilcox group and conformably under the Reklaw member of the Mount Selman formation [1].

From its outcrop-area in Nacogdoches County the Carrizo dips to the south at an average rate of about 50 feet to the mile. At the outcrop the formation is from 300 to 400 feet above sea-level. At Nacogdoches the top of the sand is about 75 feet below sea-level, and at Well 1 of the Southland Paper Mill it is about 615 feet below sea-level.

Twelve electrical logs, made in the wells of the Southland Paper Mill (Nos. 1 to 5, 23A, 30A, 290A, 292B, and 296B) and the wells of the City of Lufkin (Nos. 20 and 168) show the thickness of

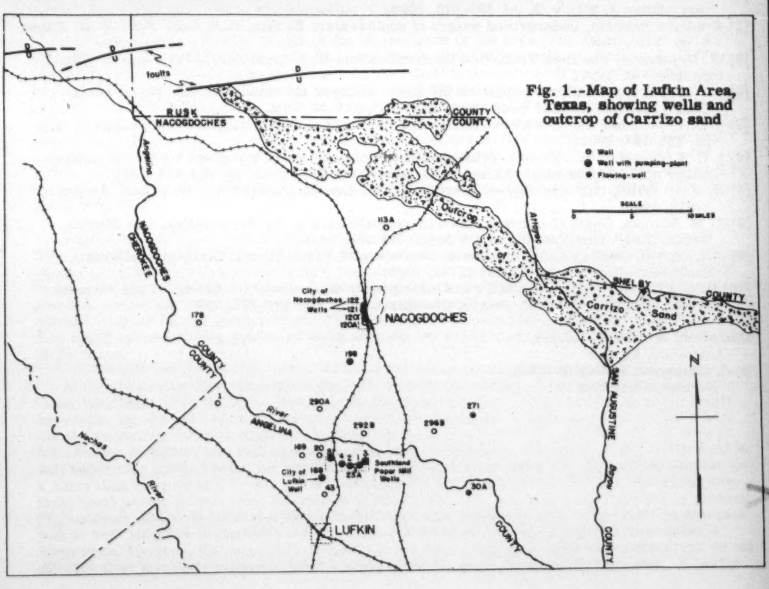

Fig. 1--Map of Lufkin Area, Texas, showing wells and outcrop of Carrizo sand

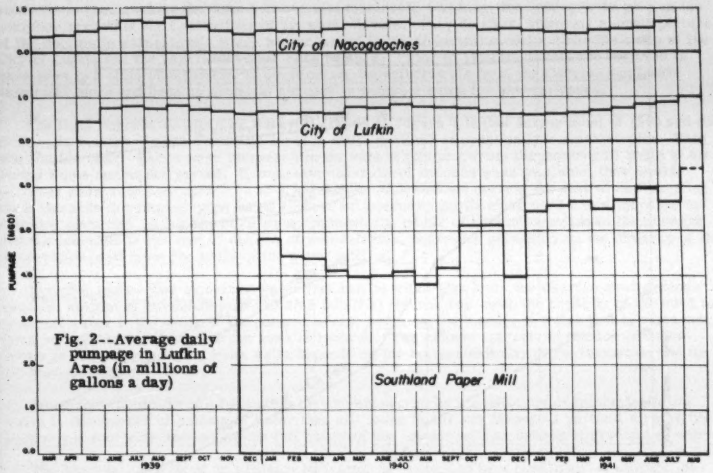

Fig. 2--Average daily pumpage in Lufkin Area (in millions of gallons a day)

the Carrizo to range from about 105 feet to 135 feet and have an approximately weighted average thickness of about 120 feet.

The Carrizo sand crops out in a continuous, gradually widening belt that extends northwestward from the Louisiana line across the northern parts of Sabine and San Augustine counties and northeastern part of Nacogdoches County, and reaches a maximum width of about eight miles in Nacogdoches County (see Fig. 1). The continuity of outcrop is broken in southeastern Rusk County on the east flank of the East-Texas syncline by a zone of faulting in which the Carrizo has been dropped and lies beneath several hundred feet of younger formations. The sand again crops out north of the fault-zone in a belt which extends to the northeast along the east flank of the syncline. To the west it dips under younger formations into the syncline and crops out on the west side of the syncline in a narrow strip which continues southwestward into South Texas. The closest point on this part of the outcrop is more than 80 miles from Lufkin.

Down dip from its outcrop the Carrizo is continuous in the Lufkin Area and apparently extends to the south a great distance beyond the area.

Pumpage--Most of the water withdrawn from the Carrizo sand in this area is pumped from the wells of the Southland Paper Mill and the cities of Lufkin and Nacogdoches (see Fig. 2). The combined rate of withdrawal from other Carrizo wells is relatively small. By far the greatest rate of withdrawal is from the five wells (Nos. 1 to 5) of the Southland Paper Mill which are about six miles northeast of Lufkin. Pumping from these wells was started in December 1939, and during the first eight months of 1940 the rate of pumping averaged a little over four million gallons a day. In the latter part of 1940 the rate of pumping was increased, and averaged about 5.7 million gallons a day during the first eight months of 1941. In Well 168, which supplies the City of Lufkin, pumping was begun early in May 1939 and averaged about 0.75 million gallons a day through August 1941. The City of Nacogdoches is supplied from two wells (Nos. 121 and 122), which have been in operation for a number of years, the rate of pumping from them during 1939, 1940, and the first eight months of 1941 averaging about 0.55 million gallons a day.

Water-levels in wells--Very few records of water-levels in wells in this area were kept before 1937. During that year a number of measurements were made by the Geological Survey [1]. Periodic measurements were begun in the latter part of 1939 and the early part of 1940, and Figure 3 shows graphs of the depth-to-water measurements made in selected observation-wells

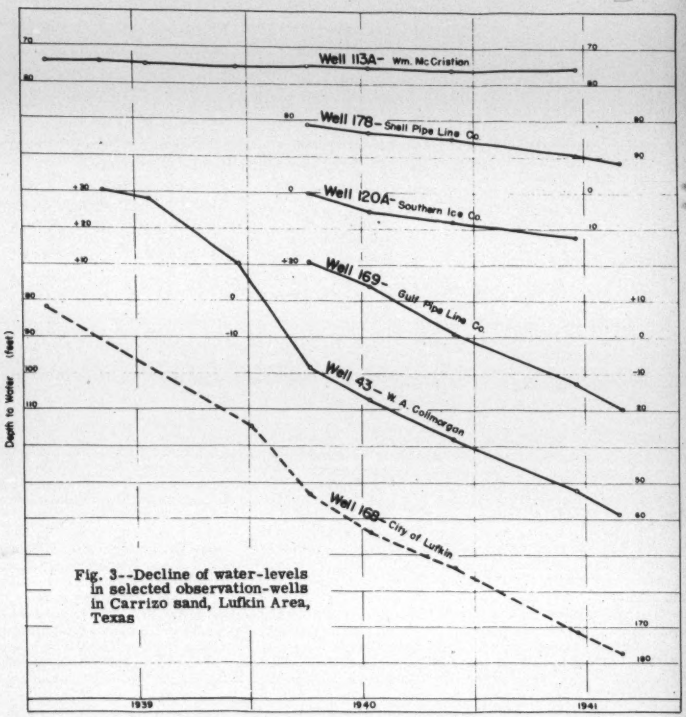

Fig. 3--Decline of water-levels in selected observation-wells in Carrizo sand, Lufkin Area, Texas

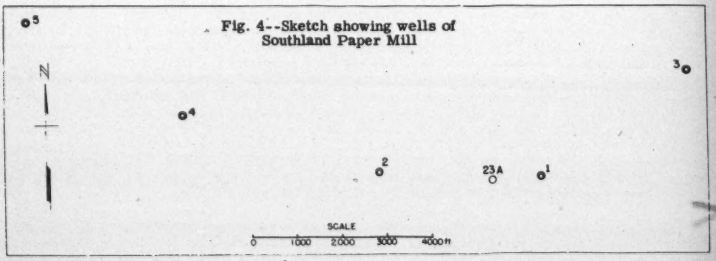

Fig. 4--Sketch showing wells of Southland Paper Mill

since then. Inasmuch as the time between measurements was long, the hydrographs give an incomplete record of the fluctuations of the water-levels. They do show, however, a rough picture of the decline in water-levels which has occurred in the observation-wells since the wells of the City of Lufkin and the paper mill were first pumped. Prior to 1939 the levels are believed to have been in a state of approximate equilibrium, as withdrawals from the Carrizo sand were small and there had been no material changes in pumping rates for several years.

The first impression given by the hydrographs in Figure 3 is that during most of 1940 and the first eight months of 1941 the water-level in wells declined at practically a constant rate. This was not the case. There were increases in the rate of pumping from the paper-mill wells at different times during the period. If complete water-level records were available, they would probably show each hydrograph to be a succession of drawdown curves, the rate of decline after each increase in pumping being rapid at first but gradually diminishing until a new increase in pumping occurred. A lag would be shown between the points of time of increase in the pumping and the increase in the rate of decline of water-levels, depending primarily on the distance of the observation-well from the wells of the paper mill.

Pumping tests--The amount of water that can be withdrawn from the Carrizo sand depends upon the amount of rainfall that percolates into it at the outcrop, upon the capacity of the sand to transmit water to the wells of the pumped areas, and upon the amount of water that is released from storage in the sand when the head is lowered. The amount and rate of decline of water-levels produced by pumping from wells depends on the transmissibility of the formation and its storage-capacity.

The transmissibility of a formation may be expressed by a coefficient of transmissibility, which is the number of gallons of water that will move in one day through a vertical strip of the aquifer one foot wide and having the full height of the aquifer with an hydraulic gradient of unity.

The storage-capacity of an artesian formation is expressed by a coefficient of storage, defined as the volume of water, measured in cubic feet, released from storage in each column of the aquifer having a base one foot square and a height equal to the thickness of the aquifer, when the artesian head is lowered one foot.

In order to determine these coefficients of the Carrizo sand, a series of pumping tests was made on the wells of the Southland Paper Mill during August and September of 1941. In these tests three or more of the wells were pumped at a time, and observations were made of fluctuations in the water-levels of the idle wells of the group produced by measured changes in the rate of pumping, which was adjusted to range between about 3,700 and 5,800 gallons a minute by turning one or more wells on or off. The length of a test, or the time during which the pumping was maintained at a given rate, varied between one and ten days, depending on the distance between the pumped and observation-wells and the methods being applied for determining the coefficients. Ten tests were made, some combinations of wells affording more determinations of coefficients than others. Figure 4 shows the relative locations of the six wells on which the tests were made.

Figure 5 is comprised of three hydrographs which represent the results of a typical test. Before the test was started Well 4 had been pumped at varying rates for several months, and at a constant rate of about 1,340 gallons a minute (1,929,600 gallons a day) for about 16 days. Water-level measurements had been made periodically for several days in wells 2 and 23A, and it has been determined from the measurements that the water-levels were in essential equilibrium in that they were declining at about the same rate. Well 4 was shut down and water-level measurements were made in the three wells at intervals as shown by the hydrographs. There were no changes in the rate of pumping from the other wells in the Southland Group either just before or during this test. The total recovery of the water-levels in any time caused by shutting down Well 4 may be obtained by adding to the amount of rise shown by the hydrograph the amount of decline which would have occurred if Well 4 had not been shut down.

These hydrographs and similar ones of other tests were analyzed by means of Thiem's formula [2] and the Theis non-equilibrium formula [3, 4, 5, 6, 7]. Both formulas assume that the aquifer is homogeneous, that its transmissibility is the same at all places, and that it is bounded by impermeable beds above and below. The non-equilibrium formula further assumes that the coefficient of storage is constant, and that the water is released from storage instantaneously with a decline in artesian head. In determining the coefficients, the Thiem formula is applied to the drawdown or recovery at equilibrium in at least two observation-wells produced by pumping or shutting down another well, while the non-equilibrium formula is applied in three ways: (1)

To the drawdown or recovery in at least two observation-wells at any time; (2) to the amount and rate of drawdown or recovery in a single observation-well; or (3) to the rate of recovery in a well which has been shut down.

Tables 1 to 3 give the coefficients of transmissibility and storage obtained by the application of these formulas to the results of the pumping tests. The Thiem formula gives coefficients of transmissibility ranging from 31,500 to 36,000 and averaging about 33,000 gallons a day per foot,

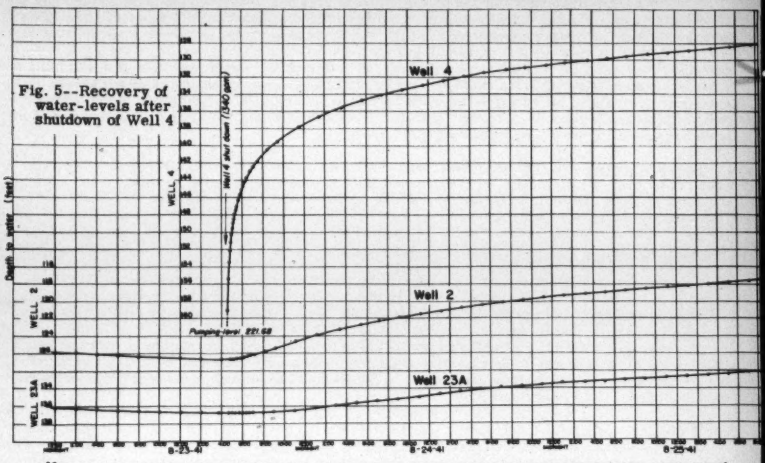

Fig. 5--Recovery of water-levels after shutdown of Well 4

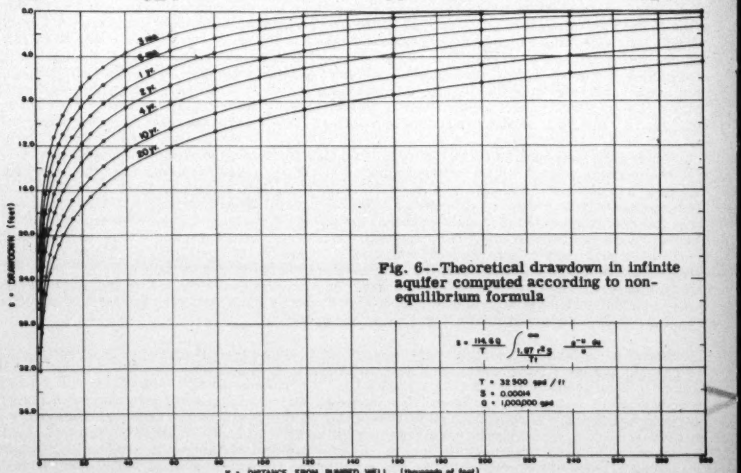

Fig. 6--Theoretical drawdown in infinite aquifer computed according to non-equilibrium formula

Table 1--Coefficients of transmissibility determined by Thiem's formula from pumping tests on wells of Paper Mill

Date of test	Pumped well turned on or off	Observation-wells	Coefficient of transmissibility (T), gpd/ft
1941			
Aug. 11-14	2 off	23A,1	33,300
Aug. 14-19	1 on	23A,2	36,000
Aug. 23-26	4 off	23A,2	31,500
Aug. 29-Sep. 1	2 on	23A,4	35,400
Sep. 1-7	1,2,3,and 5 off	23A,4	32,300
Sep. 7-20	2,4,and 5 on	23A,1	31,800
	2,4,and 5 on	23A,3	32,300
	2,4,and 5 on	1,3	32,600
	Average		33,100

Table 2--Coefficients of transmissibility and storage determined by non-equilibrium formula from pumping tests on wells of Paper Mill (interference between wells, graphical method)

Date of test	Pumped well turned on or off	Observation-well	Coefficient of transmissibility (T), gpd/ft	Average T	Coefficient of storage (S)	Average S
1941						
Aug. 2	1 off	23A	31,200		.000151	
Aug. 6-7	1 off	23A	31,500		.000149	
Aug. 5-6	1 on	23A	32,200	32,200	.000174	.000160
Aug. 14-19	1 on	23A	32,100		.000172	
Aug. 20	1 on	23A	33,800		.000156	
Aug. 14-19	1 on	2	29,700	31,400	.000135	.000143
Aug. 20	1 on	2	33,000		.000151	
Aug. 11-12	2 off	23A	34,600	33,500	.000136	.000140
Aug. 29-Sep. 1	2 on	23A	32,300		.000144	
Aug. 11-12	2 off	1	34,100	34,100	.000149	.000149
Aug. 29-Sep. 1	2 on	4	32,600	32,600	.000135	.000135
Aug. 23-26	4 off	23A	30,600	30,600	.000120	.000120
Aug. 23-26	4 off	2	30,800	30,800	.000120	.000120
	Averages			32,200		.000138

Table 3--Coefficients of transmissibility determined by non-equilibrium formula from pumping tests on wells of Paper Mill (recovery of pumped well)

Date of test	Well (shut down)	Coefficient of transmissibility (T), gpd/ft	Average T
1941			
Aug. 2	1	32,800	
Aug. 6-7	1	34,000	33,400
Aug. 11-12	2	32,800	32,800
Aug. 23-26	4	31,200	31,200
	Average		32,500

while the non-equilibrium formula gives coefficients ranging from 30,600 to 34,100 and averaging about 32,000 gallons a day per foot. The coefficients of storage range from 0.00012 to 0.00016 and average about 0.00014.

The coefficients of transmissibility and storage obtained from the individual tests agree with one another remarkably well. The Thiem and non-equilibrium formulas each give about the same coefficients of transmissibility. This agreement checks with the geologic data in showing that the Carrizo sand is remarkably uniform in thickness and character, thereby fulfilling the most important assumptions upon which the formulas are based.

Table 4--Approximate actual and theoretical recovery and drawdown of water-levels in the Paper Mill's wells during and after the general shutdown, September 1 to 19, 1941

Well	Time after wells 1, 2, 3, and 5 were shut down									
	2 days		4 days		6 days		8 days		10 days	
	Actual	Theo-retical	Actual	Theo-retical	Actual	Theo-retical	Actual	Theo-retical	Actual	Theo-retical
	Recovery in feet									
23A	39	37	50	46	58	52	62*	56	--	--
4	25	22	36	31	42	37	47*	41	--	--
	Drawdown, in feet, after well 1 was shut down and pumping was started in wells 2, 4, and 5									
23A	19	17	27	25	32	30	35	33	38	36
3	7	7	13	13	18	17	21	20	23	22

*Extrapolated.

Table 5--Approximate actual and theoretical recovery and drawdown of water-levels in outlying observation-wells during and after the general shutdown of the Paper Mill's wells, September 1 to 19, 1941

Well	Time after wells 1, 2, 3, and 5 were shut down									
	2 days		4 days		6 days		8 days		10 days	
	Actual	Theo-retical	Actual	Theo-retical	Actual	Theo-retical	Actual	Theo-retical	Actual	Theo-retical
	Recovery in feet									
168	5	5	10-1/2	11	14-1/2	15	18*	18-1/2	--	--
292B	3-1/2	4	8-1/2	9	12-1/2	13-1/2	15-1/2*	16-1/2	--	--
169	1-1/2	1-1/2	4-1/2	4-1/2	7-1/2	7-1/2	10*	10	--	--
	Drawdown, in feet, after well 1 was shut down and pumping was started in wells 2, 4, and 5									
168	7	7	13	13	17	17	20	20	22-1/2	22-1/2
292B	1-1/2	2	4-1/2	5-1/2	7	8-1/2	9-1/2	11	12	13
169	2	2	5-1/2	5-1/2	8-1/2	8-1/2	11	11	13-1/2	13-1/2

*Extrapolated.

Near the end of the tests the paper mill was shut down for a week for general repairs, and pumping was discontinued from all the wells except Well 1, which was pumped intermittently. Water-level measurements were made in the wells during the shutdown and the 12 succeeding days. Inasmuch as wells 4 and 23A were not pumping just before the shutdown, all the recovery in each was caused by shutting down the other wells. These are given in Table 4 along with the theoretical recoveries computed according to the non-equilibrium formula, using the average coefficients determined from the other pumping tests. At the end of the week's shutdown the intermittent pumping from Well 1 was stopped and constant pumping resumed from wells 2, 4, and 5. The resulting drawdowns in wells 3 and 23A are given in Table 4, together with the computed drawdowns. In determining the total actual recoveries and drawdowns it was necessary to estimate the position the water-levels would have taken had each change in pumping rate not occurred; and because Well 1 was pumped intermittently and computations were based on the assumption that it was pumped at a constant rate, it was also necessary to apply an additional small correction to the estimated actual recoveries and drawdowns in order to compare them with the computed values. The recoveries and drawdowns thus determined compare favorably with the computed values. This was to be expected, because the coefficients used to compute the theoretical values were obtained from pumping tests made on most of the wells concerned in the computations.

Measurements were also made during and after the seven-day shutdown in observation-wells at distances of several miles from the nearest Southland well. The approximate recoveries and drawdowns in wells 168, 169, and 292B are given in Table 5, together with the theoretical values computed by means of the non-equilibrium formula. The close agreement between actual and theoretical recoveries and drawdowns in these wells tends to show that the non-equilibrium formula and the average coefficients used apply to the Carrizo sand at least within the range of distance and time covered.

Theoretical check of water-level declines since 1939--The non-equilibrium formula was used

with the average coefficients of transmissibility and storage to compute the declines in water-levels which occurred over the area between 1939 and 1941. Average rates of pumping were used and it was assumed that the water-table in the outcrop remained at a constant level. Accurate water-level records for 1939 are available only for Well 43. The computed decline in this well between May 1939 and June 1941 amounts to 74 feet, whereas the actual decline was about 83 feet. The difference is within the limits to be expected from meager water-level data and estimates of changes in pumping rates. For the other wells it was found that the declines during the latter part of 1940 and during 1941 correspond closely with the computed drawdowns, but sufficient water-level data are not available for 1939 and early 1940, when the greater parts of the declines caused by the new wells occurred, to permit comparison of the total declines.

Theoretical drawdown-curves for infinite aquifer--The curves in Figure 6 were computed by the non-equilibrium formula, and show the drawdown at the end of different periods of pumping produced at various distances from a well pumped at the rate of one million gallons a day. An artesian aquifer of infinite areal extent is assumed, having coefficients of transmissibility and storage of 32,500 gallons a day per foot and 0.00014, respectively. The coefficients used are averages of those determined from the pumping tests.

Boundaries of Carrizo sand--Before an estimate can be made of the decline in water-levels in an aquifer caused by the withdrawal of a known amount of water, its lateral boundaries, as well as its thickness, must be ascertained. In an aquifer such as the Carrizo sand in the Lufkin Area, which is pumped at a distance of many miles from the outcrop, the water-levels in wells are not influenced much by the position of the area of recharge during the first few months or even years after pumping is begun; but, as time goes on, this becomes more and more a determining factor of the decline in water-levels. At first, therefore, inaccuracies in the location and extent of the outcrop-area may not cause much divergence between actual drawdowns and computed drawdowns, but, ultimately, may result in greater or smaller declines than predicted.

In computing drawdowns it is assumed that the outcrop, or intake-area, of the aquifer is a line of infinite length and that the water-table along the line is kept at a constant level. A recharge-well is assumed to be placed on a line drawn through the actual well, perpendicular to the line of intake, at an equal distance on the opposite side of the intake. The net drawdown for any point in the aquifer is the algebraic sum of the drawdown produced by pumping the actual well and the rise in water-level produced by the hypothetical recharge-well, these being computed on the assumption of an infinite aquifer. The computed decline is always zero along the line of outcrop.

Actually an outcrop of infinite length does not exist anywhere. In this area the syncline and faults which displace the outcrop of the Carrizo may essentially cause the absence of the line-source to the west. Theis has devised a method[8] based on his non-equilibrium formula by which it is possible to compute the amount of water coming at any time from each portion of an infinite line-source. If in the Lufkin Area the line-source is considered to be absent west of the faulting (see Fig. 1), it is computed that a portion of the source is missing which would at equilibrium yield about one-fourth of the total demand and that the draft on the remainder of the line, therefore, is about one-third more than it would be if the line were of infinite length. Thus, the decline caused by pumping a well will be greater than is computed from the infinite line-formula. The proportionate excess in the true drawdown over the computed drawdown should be at a maximum near the outcrop and decrease toward the well, and the excess should be greater in a westerly direction from the pumped well than toward the east.

Theis [9] has also adapted an equation derived by Muskat [10] to the determination of drawdowns in the Lufkin Area. He found by this equation that the computed drawdown at Nacogdoches at equilibrium, assuming an infinite line-source, caused by the paper mill's pumping must be increased by about 15 to 20 per cent to make up for the lack of an effective line-source west of the faulting. Further computations show that the proportionate correction which should be applied becomes slightly smaller toward the paper-mill wells and larger toward the line-source.

Recharge--Computations based on the Theis non-equilibrium formula indicate that most of the water withdrawn from the Carrizo sand by the wells of the Southland Paper Mill and the one of the City of Lufkin during the past two years, and a large part of that now being pumped, has come, and is coming, from artesian storage. If equilibrium is to be reached, all of the water must eventually come from recharge at the outcrop. Although the 1937 report [1] states that there is rejected recharge on the outcrop-area of the Carrizo sand in the form of springs and seeps, it is not known whether the springs and seeps will be shut off and recharge to the sand increased sufficiently to supply these developments; and, similarly, it is not known whether there is sufficient available

recharge for an increase in pumping. Natural discharge from the Carrizo down the dip to the south and southeast of Lufkin has been computed to be rather small [1], and it is not probable that much of it will be salvaged by pumping from wells.

Conclusions--The Carrizo sand is unusually uniform in thickness and character in the Lufkin Area, and, therefore, fulfills unusually well the fundamental assumptions made in the Thiem's and non-equilibrium formulas. The individual coefficients of transmissibility and storage determined from the pumping tests at the Southland Paper Mill are in remarkably close agreement, and tend to prove that both formulas are applicable to the area.

As well as can be determined from the meager water-level data available, the declines in water-levels between 1939 and 1941 in widely-spaced observation-wells of the Lufkin Area, caused by pumping the well of the City of Lufkin and the five wells of the Southland Paper Mill, agree with the drawdowns computed by the non-equilibrium formula, using the average coefficients determined from the pumping tests.

The data indicate that the Theis non-equilibrium formula may be used with the average coefficients determined from the pumping tests to estimate, within reasonably wide limits, future drawdowns of water-levels in wells in this area, at least for a few years, which will occur if the present pumping rates are maintained--and to estimate the drawdowns which may be produced by increasing these rates. An allowance must be made in these estimates, however, for the lack of an effective outcrop-area west of the faulting in Rusk County.

Acknowledgments--W. N. White was in direct charge of the investigation and assisted in the preparation of this paper. C. V. Theis aided in interpreting and applying the results of the pumping tests. The staff of the Southland Paper Mill and L. G. Davis assisted in making the tests; and the following persons and organizations furnished various data and made their wells available for observation: Southland Paper Mills, Inc.; City of Lufkin; City of Nacogdoches; Gulf Refining Company; Shell Pipe Line Company; Piney Woods Country Club; W. A. Collmorgan; L. C. Jacobs; and Mr. McKnight.

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U. S. Geological Survey,
Lufkin, Texas

RECHARGE TO GROUND-WATER FROM FLOODS IN A TYPICAL DESERT WASH, PINAL COUNTY, ARIZONA

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(Published with the approval of the Director, Geological Survey, United States Department of the Interior)

Statement of the problem

Queen Creek, considered in this paper, is a typical large desert wash. It rises in the Pinal

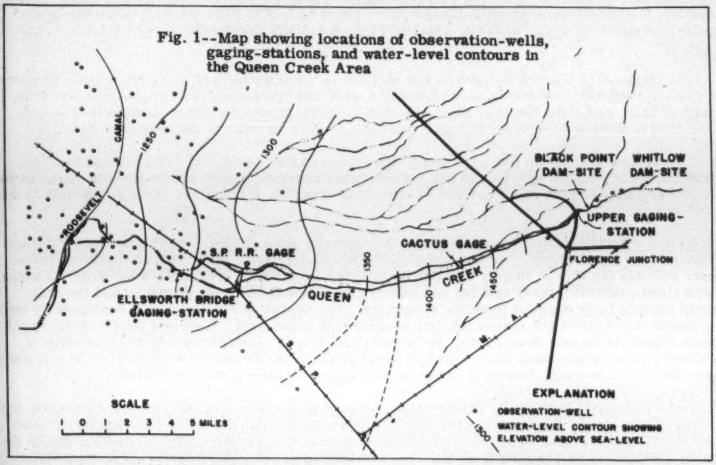

Fig. 1--Map showing locations of observation-wells, gaging-stations, and water-level contours in the Queen Creek Area

Mountains near the mining town of Superior and enters the outwash-plain at Black Point about three miles north of Florence Junction (see Fig. 1). Thence it passes over the desert in a southwesterly direction toward Chandler, spreads over the lowlands, and disappears. The flow of the stream consists almost entirely of storm-water and is of the quick, flashy type common to the deserts of the Southwest. In ordinary years the stream is dry most of the time. Formerly the flood-waters spread over the floor of the desert and did no harm. Now, however, they invade highly cultivated lands that are irrigated with water from Salt River or from wells, and cause serious damage to both crops and canals. The damage could be prevented by storing the storm-waters in a reservoir formed by a dam at or above Black Point.

The purpose of the investigation was to determine the probable effect of control by this reservoir on normal ground-water recharge from the stream in the desert stretch, the size of the stream which should be released from the reservoir to give maximum recharge, and the practicability of water-spreading operations to increase the normal recharge. The investigation comprised a part of the studies of the ground-water resources of Arizona that are being undertaken by the Geological Survey of the United States Department of the Interior in cooperation with the Arizona State Water Commissioner and Corps of Engineers of the United States Army. These studies are under the general direction of S. F. Turner. The field-work in the Queen Creek area was started August 5, 1939, and was done by H. M. Babcock and E. M. Cushing under the direction of L. C. Halpenny; the geology was studied by R. B. Morrison.

Geology

In the mountains Queen Creek flows over relatively impermeable schists, granites, and other

volcanic rocks and loses no appreciable amount of water to deep underground storage.

Older alluvium--About a mile west of Black Point the creek passes from the mountains to the alluvial slope of the desert plain. Near the mountains its present flood-plain is entrenched about 70 feet below the surface of its old alluvial fan. This fan coalesces with those of neighboring washes to form a piedmont plain. A well-defined terrace borders the flood-plain which at Black Point is about 55 feet below the piedmont plain. Westward from Black Point the scarps separating the three surfaces (piedmont plain, stream-terrace, and present flood-plain) become lower until the surfaces converge into a nearly level plain.

West from Black Point for two or three miles the piedmont plain is underlain by a rock-cut pediment that is only partly buried beneath relatively shallow alluvial fill. A little farther west, however, the water-level in wells changes from about 60 feet to over 400 feet below the land-surface, suggesting the presence of a buried fault-scarp and thicker deposits of alluvium to the west.

The piedmont and terrace deposits are similar in lithology and are grouped together as older alluvium. Both are moderately well to poorly sorted and contain aggregates of small boulders, cobbles, sand, and silt. Westward this material is finer, though not appreciably better sorted. They appear to have been deposited under conditions such as exist at the present time.

Caliche cementation in the upper six to ten feet of gravel underlying the piedmont plain retards the penetration of water from the surface into the gravel except where streams have cut below the caliche. Caliche is not well developed on the stream-terrace and is usually absent in the flood-plain.

Recent alluvium--Recent stream-deposits of gravel, sand, and silt cover the older alluvium in the present flood-plain. The torrential flash-floods ordinarily carry a heavy bed-load in the upper reaches but this is rapidly dropped as the stream-gradient decreases westward. As a result a flood-plain with many shifting and interlacing channels has been produced and the sediments become finer outward from the mountains. The degree of sorting varies considerably with the floods that deposit the sediments, but in general it is not high. The most poorly-sorted sediments appear to be laid down during the larger flash-floods. During periods of steady flow of relatively clear water (such as sometimes occur after floods caused by winter rains) the channel-materials are reworked, becoming better sorted and consequently more permeable.

In the first few miles of the desert section, the flood-plain is relatively constant in width, but westward from there it widens. In the upper reaches the bed of the creek is composed of sand, gravel, and boulders (see Fig. 2). Farther down it is composed principally of sand, although the smaller channel beds are silty (see Fig. 3). The flood-plain outside of the present channels is covered by one to several feet of silt, usually underlain by coarse deposits that represent earlier channel-deposits. Still farther down the silt-mantle thickens and contains little sand or gravel (see Fig. 4).

Ground-water recharge

Queen Creek is influent throughout its entire course below the Black Point Dam site. Minor floods disappear within a short distance. Larger floods cross the area with gradually diminishing losses as the channel-deposits and older alluvium become finer, and the part of the flow that is not absorbed spreads out over the relatively impermeable silt-covered plain at the lower end of the creek and is lost by evaporation and transpiration.

Two gaging-stations have been maintained in connection with the Queen Creek investigation--the upper station about three-fourths of a mile below Black Point and the lower one at the county highway bridge, about 20 miles below Black Point. An intermediate staff-gage designated the Cactus gage also was maintained for a time. In the discussion that follows, the upstream station is designated as the Upper Gaging-Station and the downstream station as the Ellsworth Bridge Gaging-Station. The Upper Station was established in August 1939, and the Ellsworth Bridge Station somewhat later. The first year of their operation was exceptionally dry and the second year exceptionally wet. This afforded an opportunity for comparison of the rate of seepage-loss under these two extreme types of climate. Table 1 gives a summary of losses between the two gaging-stations from 17 floods that occurred between February 12, 1940, and March 12-18, 1941. During the two years floods with peak-discharge, ranging from a few second-feet to 13,000 second-feet, were recorded at the upper station (one second-foot equals 448.83 gallons a minute).

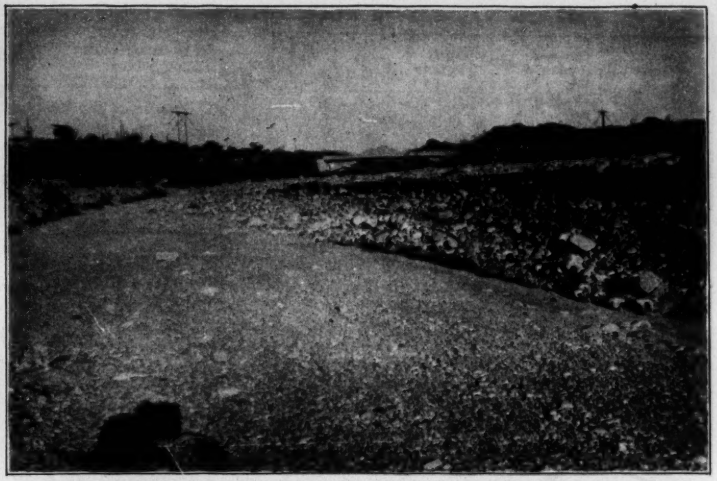

Fig. 2--Channel of Queen Creek near the Upper Gaging-Station

Fig. 3--Channel of Queen Creek near Ellsworth Bridge Gaging-Station

Fig. 4--Cracks in silt deposits in Queen Creek flood-plain 2.5 miles below the Ellsworth Bridge Gaging-Station

Table 1--Summary of losses from floods on Queen Creek

[Observations at Upper Gaging-Station (U.G.-S.) and Ellsworth Bridge Gaging-Station (E.B.G.-S.)]

Date	Peak-flow at		Total discharge at		Total loss	Length of flow at		Rate of loss
	U.G.-S.	E.B.G.-S.	U.G.-S.	E.B.G.-S.		U.G.-S.	E.B.G.-S.	
	sec-ft	sec-ft	ac-ft	ac-ft	ac-ft	hr	hr	ft/day
Feb. 12, 1940	170	30	68.8	11.5	57.3	20	12	0.73
July 24-25, 1940	170	28	25.6	4.9	20.7	14	8	0.71
Aug. 3-4, 1940	700	214	58.4	45.0	13.4	16	16	0.14
Oct. 5, 1940	650	365	152	65.7	86.3	12	9	1.03
Oct. 27, 1940	994	395	244	149	95	25	26	0.46
Nov. 18-19, 1940	3,730	2,500	1,880	1,260	620	33	33	1.16
Dec. 11, 1940	1,790	795	309	144	165	18	18	1.17
Dec. 12, 1940	4,710	3,250	1,340	1,060	280	15	15	0.86
Dec. 24, 1940	8,020	4,340	2,680	1,830	850	28	24	1.31
Dec. 30, 1940, to Jan. 2, 1941	9,880	5,700	12,000	8,500	3,500	140	134	1.37
Jan. 12-13, 1941	5,990	3,300	2,700	1,380	1,320	48	37	1.62
Jan. 24-25, 1941	800	535	569	146	423	27	24	1.37
Jan. 28, 1941	3,340	1,160	1,270	321	949	47	31	1.74
Feb. 7-8, 1941	3,080	1,370	1,900	628	1,272	43	34	2.09
Feb. 24-25, 1941	4,240	3,220	3,090	2,360	730	54	54	0.75
Mar. 1-2, 1941	4,020	2,380	1,480	832	647	21	16	1.78
Mar. 12-18, 1941	7,420	5,420	15,600	9,320	6,280	138	126	1.71

Altogether during the period 64,300 acre-feet of water passed the Upper Gaging-Station while 32,100 acre-feet passed the Ellsworth Bridge Gaging-Station, showing that about one-half of the total runoff was recharged to ground-water (one acre-foot equals 325,851 gallons).

Table 2--Details of runs of seepage-measurements on Queen Creek, 1941

Date	Description of measuring point	Length of reach	Distance from U.G.-S.	Discharge	Loss	Wetted area	Rate of loss	Average temp.	Rate of loss corr. to 60° F
1941		miles	miles	sec.ft	sec-ft	acres	ft/day	°F	ft/day
Jan. 24	1.5 miles above Upper Gaging-Station	---	1.5	3.32	---	---	---	--	---
	Reach	1.1	---	---	3.32	2.04	3.23	54[a]	3.52
	0.4 mile above Upper Gaging-Station	---	0.4	0.0	---	---	---	--	---
Jan. 29	Upper Gaging-Station	---	0.0	120	---	---	---	--	---
	Reach	2.1	---	---	61.8	18.8	6.51	64[a]	6.18
	Bridge over U. S. Highway 80	---	2.1	58.2	---	---	---	--	---
	Reach	4.4	---	---	47.3	16.0	5.86	72[a]	4.98
	6.5 mile cross-section	---	6.5	10.9	---	---	---	--	---
Jan. 30	Upper Gaging-Station	---	0.0	61.9	---	---	---	--	---
	Reach	2.1	---	---	50.1	14.0	7.10	66[a]	6.53
	Bridge over U. S. Highway 80	---	2.1	11.8	---	---	---	--	---
	Reach	1.6	---	---	11.8	4.85	4.83	69[a]	4.25
	1.6 miles below bridge over U. S. Highway 80	---	3.7	0.0	---	---	---	--	---
Jan. 31	Upper Gaging-Station	---	0.0	38.4	---	---	---	--	---
	Reach	2.1	---	---	38.4	11.0	6.96	61[a]	6.82
	Bridge over U. S. Highway 80	---	2.1	0.0	---	---	---	--	---
Feb. 1	Upper Gaging-Station	---	0.0	21.8	---	---	---	--	---
	Reach	1.2	---	---	21.8	5.67	7.63	66[a]	6.94
	1.2 miles below Upper Gaging-Station	---	1.2	0.0	---	---	---	--	---
Mar. 17	S. P. R. R. Bridge No. 2	---	16.7	38.8	---	---	---	--	---
	Reach	1.3	---	---	16.1	5.28	6.05	58[a]	6.23
	Hurt's Crossing	---	18.0	22.7	---	---	---	--	---
	Reach	1.0	---	---	2.9	5.47	1.16	62[a]	1.13
	Ellsworth Bridge Gaging-Station	---	19.0	19.8	---	---	---	--	---
	1.6 miles below I. C. Ranch	---	13.6	19.2	---	---	---	--	---
	Reach	1.8	---	---	12.58	10.7	2.33	73[a]	2.00
	3.4 miles below I. C. Ranch	---	15.4	6.62	---	---	---	--	---
	Reach	1.3	---	---	5.68	2.36	4.77	69[a]	4.22
	S. P. R. R. Bridge No. 2	---	16.7	0.94	---	---	---	--	---
Mar. 18	Upper Gaging-Station	---	0.0	246	---	---	---	--	---
	Reach	4.5	---	---	131	49.1	5.29	57	5.53
	4.5 mile cross-section	---	4.5	115	---	---	---	--	---
	Reach	1.0	---	---	24.8	9.09	5.41	82	5.25
	5.5 mile cross-section	---	5.5	90.2	---	---	---	--	---
	Reach	2.3	---	---	51.2	13.9	7.29	68	6.49
	7.75 mile cross-section	---	7.8	39.0	---	---	---	--	---
	Reach	1.2	---	---	18.7	5.09	7.29	72	6.12
	9 mile cross-section	---	9.0	20.3	---	---	---	--	---
	Reach	3.0	---	---	20.3	7.27	5.54	77[a]	4.35
	I. C. Ranch	---	12.0	0.0	---	---	---	--	---
Mar. 23	1.5 miles above Upper Gaging-Station	---	1.5	83.6	---	---	---	--	---
	Reach	1.5	---	---	16.4	11.8	2.75	71	2.34
	Upper Gaging-Station	---	0.0	67.2	---	---	---	--	---
	Reach	2.1	---	---	54.7	14.5	7.48	76[a]	5.98
	U. S. Highway 80 Bridge	---	2.1	12.5	---	---	---	--	---
Mar. 25	1.5 miles above Upper Gaging-Station	---	1.5	67.8	---	---	---	--	---
	Reach	1.5	---	---	16.4	11.3	2.89	71	2.46
	Upper Gaging-Station	---	0.0	51.4	---	---	---	--	---
	Reach	2.1	---	---	51.4	12.2	8.34	74	6.84
	U. S. Highway 80 Bridge	---	2.1	0.0	---	---	---	--	---
Mar. 29	1.5 miles above Upper Gaging-Station	---	1.5	39.0	---	---	---	--	---
	Reach	1.5	---	---	20.3	8.55	4.71	72	4.00
	Upper Gaging-Station	---	0.0	18.7	---	---	---	--	---
	Reach	0.7	---	---	18.7	2.16	17.1	70	14.77
	0.7 mile below Upper Gaging-Station	---	0.67	0.0	---	---	---	--	---

[a]Estimated.

In order to compute the rate of infiltration between the gaging-stations, the areas wetted by floods of different magnitudes were estimated. This was done by running traverses across the flood-plain at intervals of one-half mile and estimating the aggregate widths of the channels wetted by flows of 10, 25, 100, 1,000, and 2,000 second-feet, and by a very large flood on August 6, 1939. From these data the arithmetical average of widths wetted by each flow and the number of acres wetted by flows of various magnitude were estimated. The areas wetted were plotted against the discharge in second-feet for each hour of flow.

The computed average rate of infiltration over the wetted area for the different floods varied from 0.14 to 2.09 feet per day and averaged 1.08 feet per day (see Table 1). The rate of infiltration for the summer-type flash-floods was less and showed a wider range than those for the winter-type floods. This is attributed to the fact that floods of the summer type are of shorter duration and on the average carry more silt than those of the winter type. During water-spreading operations in the upper Santa Ana River, California, Mitchelson and Muckel [see 1 of "References" at end of paper] demonstrated that the rate of infiltration decreased appreciably with the application of dirty or silt-laden water. The wide range in the computed rate of infiltration for the summer-type floods on Queen Creek may have been due largely to inability to measure these floods accurately.

The unusually heavy rainfall during the winter of 1940-41 aided the growth of a large amount of heavy vegetation in the drainage-basin of Queen Creek. This vegetation decreased the silt-load carried by Queen Creek, which probably caused the rate of infiltration to increase during the winter and spring.

Runs of seepage-measurements--Due to the unusually heavy rainfall, water flowed continuously past the Upper Gaging-Station and was comparatively clear a considerable part of the time from January 24 to April 24, 1941. On two occasions during this period about 500 second-feet of fairly clear water, that passed the Upper Gaging-Station, caused no flow at the Ellsworth Bridge Gaging-Station. The rate of infiltration on these two occasions was computed as about three feet a day. Eleven runs of seepage-measurements were made during this period between January 24 and March 29. In these runs the discharge of the creek was measured at several selected points in turn, the stream-gager moving in a downstream direction. The difference in discharge between any two of these points represented approximately the amount of water lost by infiltration in the intervening reach. The distance between the gaging-points was measured and the area wetted in each of these reaches was computed. From these data the average rate of loss in depth of water in feet a day over the wetted area was computed. The results of the seepage-measurements and computations from them are given in Table 2.

A comparison of the rates of infiltration over the wetted area between the gaging-stations during floods with the rates determined from the seepage-measurements during moderate to low flows of comparatively clear water is instructive. The average for the floods over the entire stretch was only about one foot a day, while the average for the clear water in the individual parts of the stretch during the seepage-runs was more than four feet a day. The smaller rate of infiltration during the floods was due in part to the large silt-load, carried during the early stages of the flood, and in part to the spreading of the flood-water during large flows upon silty rather impermeable material in areas outside the channels.

In the seepage-measurements it was noted that the rate of infiltration progressively decreased in a downstream direction as the material in the channel-bottom became progressively finer. It was also observed that during continuous flows of clear water after floods, the rate of infiltration increased with time. For a 2.1-mile stretch between the Upper Gaging-Station and the highway bridge it was 6.18 feet a day on January 29, 6.53 feet a day on January 30, and 6.82 feet a day on January 31, 1941. On March 23, 1941, several days after a large flood, the rate of infiltration for the same reach was 5.98 feet a day, and on March 25, 6.84 feet a day. In each case the water was clear at the Upper Gaging-Station but became progressively muddier downstream, showing that the clear water had sufficient velocity to transport the fine material, leaving the coarser and more permeable material. It is believed that a controlled steady flow of fairly clear water would soon wash out most of the fine material, and that under control the flow at the Upper Gaging-Station could be reduced sufficiently to prevent any water from flowing past the Ellsworth Bridge Gaging-Station and being lost on the silt-covered areas below.

Rise in water-levels--Wells in the desert plain near Queen Creek showed considerable rise in water-level during the early spring of 1941 as a result of recharge from the winter and spring runoff, whereas wells at a considerable distance from the creek showed very little rise.

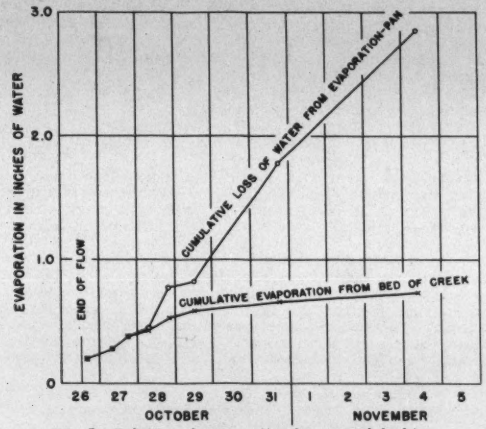

Fig. 5--Relation of evaporation from creek bed to evaporation from sunken land-pan

Table 3--Rates at which water-surfaces of pools were lowered after surface-flow ceased

Date of flood	Pool	Rate of infiltration		Length of test
		Initial rate	Final rate	
1939		ft/day	ft/day	hours
Sep. 13	1	0.76	---	5
	2	2.76	---	5
	3	0.24	---	12
	4	0.72	0.60	34
Sep. 16-17	3	0.26	0.22	38
	4	0.76	0.98[a]	26
Oct. 26-27	3	0.38	0.26	123
	4	1.20	0.88	17
	5	0.52	0.62	6
	6	1.04	---	3
	7	0.18	0.16	27
	8	1.32	---	5
	9	0.64	0.64	16
	10	1.66	---	3
	11	0.16	0.44	27
	12	1.82	---	3
	13	0.30	0.40	15
	14	1.82	1.78	15
	15	0.16	0.10	45
Nov. 29	16	1.66	1.86	6
	17	0.66	0.58	5
Average		0.91	---	--

[a]Silt-bottom disturbed by cattle wading in pool.

Infiltration from pools--The rate of decline in water-levels was measured in pools that remained in the channels after floods in an effort to check the coefficients of infiltration determined from stream-gaging. The results are summarized in Table 3. The rate of lowering ranged from a maximum of 2.76 feet a day to a minimum of 0.16 foot a day, the initial rate averaging 0.91 foot a day. This is fairly close to the average coefficient of infiltration of 1.08 feet a day computed from the flood-measurements.

Evaporation-losses from bed of creek--Following a flood in the comparatively dry fall of 1939, several small containers filled with stream-bed material and a water-evaporation pan of the Colorado sunken-pan type were installed in the bed of the creek. The loss in moisture from the containers was approximately equal to the loss from the evaporation pan for the first 36 hours after the flood, but subsequently it decreased rapidly (see Fig. 5). This indicates that the amount of water required to satisfy the deficiency of moisture in the stream-bed before water could penetrate to the underground reservoir was not very large.

Conclusions

The principal recharge to ground-water in the desert region of the Southwest is from occasional flash-floods in the mountain streams and washes. Recharge occurs by infiltration into the stream-beds where they cross the desert plains. In the lowermost reaches of these streams and washes, as in Queen Creek, the flood-water generally spreads over the surface of silt-covered playas and is lost by evaporation. In the two years of record about half of the flow of Queen Creek at the mouth of its canyon was recharged to ground-water. It might be possible, however, by the construction of a flood-control dam to put practically all the water into ground-water storage. A dam at or above Black Point would release flood-water of comparatively low silt-content at a nearly uniform rate and would extend the flow over a much longer period than now. It is believed that with all floods controlled and only small flows released there would be little tendency for the bottom of the Queen Creek Channel to become sealed with silt. In fact, with the release of clear water, the channel would be cleaned of a part of the fine materials that are now present.

The investigation indicates that the largest discharge that could be released from the Upper Gaging-Station with no flow past the Ellsworth Bridge Gaging-Station is about 500 second-feet, if most of the silt has settled out before the water leaves the reservoir. It seems probable, however, that this could be increased to as much as 1,000 second-feet by the installation and operation of artificial spreading-devices in the channels of Queen Creek.

In Arizona, as in most other parts of the Southwest, the greater part of the surface-water resources that it is practicable to develop, and a large part of the ground-water resources are utilized. At the present rate of development the limit of the ground-water supplies will soon be reached. It should be possible to extend this limit in some localities by artificial recharge of water, as has been done with considerable success in Southern California, thus utilizing water that otherwise would be wasted by evaporation on the desert.

Reference

[1] A. T. Mitchelson and Dean C. Muckel, Spreading water for storage underground, U. S. Dep. Agric., Tech. Bull. 578, December 1937, p. 16.

U. S. Geological Survey,
Washington, D. C.

SECTION OF HYDROLOGY
AMERICAN GEOPHYSICAL UNION

REPORTS AND PAPERS

JOINT REGIONAL MEETING
WITH WESTERN INTERSTATE
SNOW-SURVEY CONFERENCE
PASADENA, CALIFORNIA
JANUARY 16-17, 1942

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INTRODUCTION

This meeting of the South Pacific Coast Area for the Section of Hydrology of the American Geophysical Union is the eighth regional meeting to be held in Southern California and the second one in Pasadena, the first being held in 1936. While the South Pacific Coast Area includes more than California members, perhaps the reason for holding the meetings in California is because of the very high percentage of the membership in this State. The aim, however, has been to make the meetings regional in character. The attendance of members outside of California is evidence that the meetings have accomplished this purpose. Holding meetings in the northern part of the State one year and in the southern part the next has been the policy of the South Pacific Regional Committee. The meetings are under the direction of the South Pacific Committee composed of the following members:

H. F. Blaney	S. T. Harding	Samuel B. Morris	Franklin Thomas
J. E. Church	M. R. Huberty	M. P. O'Brien	F. J. Veihmeyer
Harold Conkling	Charles J. Kraebel	H. C. Schwalen	H. A. Wadsworth
Harry C. Dukes	Charles H. Lee	Fred C. Scobey	Baldwin M. Woods
C. C. Elder			

The facilities of the California Institute of Technology through the courtesy of Professor FRANK THOMAS was placed at the disposal of the Committee for this meeting. Professor Thomas was local chairman and made all the arrangements for the meeting and organized the program. The program consisted of three half-day sessions, two on January 16 and one on the morning of January 17, 1942. The two sessions on Friday, January 16, comprised discussions of the results of investigations of hydraulic and hydrologic import from laboratories in the South Pacific Area. The session on the forenoon of January 17 included papers dealing with the hydrology of Southern California, particularly relating to the exceptionally high precipitation of the season 1940-41.

We are further indebted to Professor Thomas for a most interesting and instructive trip to the water-softening plant of the Metropolitan Water District of Southern California. The operation of the plant was demonstrated by William Aultman, Superintendent of the Treatment-Plant.

The attendance at the Pasadena Meeting was not as great as that at previous South Pacific meetings. The names of those who registered totaled 126, a satisfactory number considering these troubled times. There were registrations from neighboring States but, of course, the greater portion of those in attendance were from California.

F. J. VEIHMEYER

EXPERIMENTAL EVIDENCE ON THE EFFECT OF SUSPENDED SEDIMENT ON FLOW-CHARACTERISTICS

Vito A. Vanoni

(Abstract)

The results of laboratory experiments are presented which show that the addition of suspended load to a flow tends to reduce the apparent friction-factor, thus causing the flow-velocity to increase. In the laboratory experiments this effect increases up to sediment-concentrations of 1.5 per cent by weight, which is the highest reached. The problem is analyzed in terms of the turbulent transfer-mechanism, and the action of the sediment in increasing the flow-velocity is explained by its effect in reducing the turbulence. Evidence is presented that actions similar to those observed in water-flows carrying suspended loads are also found in other fluid-flows in which a density-gradient exists. Concentration-gradients across flows are discussed, particularly in regard to their possible relation to the secondary currents existing in natural streams.

Soil Conservation Service,
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SCOUR-CONTROL AND SCOUR-RESISTANT DESIGN FOR HYDRAULIC STRUCTURES

Brooks T. Morris

Introduction--There now exists in theoretical analyses, in laboratory findings, and in conventional engineering-design practice, a skeleton of facts on which a rational scour-control procedure can be based. The writer has assembled these facts and stated them in as straightforward a manner as, he believes, is consistent with current knowledge. Examples of the manner in which the analysis is taken into account in ordinary engineering design are given in support thereof.

Scour--Scour-control procedures should be planned with attention to the details of the scour-phenomenon itself. Scour may be defined as the deepening, widening, or shifting of stream-channels under the influence of locally concentrated attack by running water. It is important in hydraulic design primarily in its effect on the safety of structures founded on erodible materials. For instance, if a stream-channel be deepened by scour below a dam, the downstream toe of the structure, normally a point of high stress-intensity, may be undermined by caving, or by percolation-flow, or by both. Such undermining can bring about disintegration of the structure or its foundation and, eventually, the dislodgment, overturning, or collapse of the dam.

Scour can be dangerous to the abutments of a dam, as well. If the channel be widened by scour, caving of the banks may weaken the natural abutments or may shorten the percolation-paths through them sufficiently to bring about sloughing, piping, and complete destruction. Although undermining by scour is only one cause of dam or abutment failure, lack of attention to scour-control has ranked with other types of spillway and foundation inadequacy as a major cause of damage or failure. As the "tighter" dam sites are used up so that more and more structures must be built on permeable foundations, scour-control will become more and more important to dam safety.

Although, scour previously has been treated primarily as a matter of the hydraulics of structures, current practice is to treat scour-control as a problem in the dynamics of streams. Scour is an exceedingly difficult phenomenon to observe in its active phase in nature. Normally, we can observe only its effects after passage of a flood or damage to a structure. It is appropriate, therefore, that specific scour-problems be studied in the hydraulic laboratory and that the general problem be analyzed as a phase of the mechanics of sediment-transportation, a branch of science in which basic data are established in the hydraulic laboratory as well as through field-observation.

From the viewpoint of sediment-transportation mechanics, scour may be considered to be the removal of sediment because of local and variable excess of entrainment over deposition. Three possibilities exist concerning the rate of growth of scour-holes; either this excess will increase with the size of the scour-hole, it will remain constant, or it will decrease. The first case is one of instability; sudden and rapid growth will continue as long as that case applies. But that same rapid growth will quickly alter the flow and bring to an end the conditions of the first case.

The second possibility leads to a constant rate of growth. The third one, ordinarily that most important in the production of large scour-holes, yields a steadily decreasing rate of scour-hole growth in which a condition of equilibrium between entrainment and deposition is approached. At this equilibrium-condition scour ceases and sediment is continuously interchanged between the bed and the stream.

Factors in scour control--The factors that control the ability of a stream to scour and that are significant to our problem may be listed as follows: (1) The amount of sediment brought into the region of scouring action by the stream; (2) the sediment-carrying capacity of the flow in the downstream channel; (3) the resistance of the bed- and bank-materials to dislodgment and entrainment; (4) the mixing or sediment-suspending power of the eddies produced in the scour-zone; and (5) the velocity of flow through the scour-zone.

At present the influence of each of these factors is but partly understood. Their evaluation is absorbing the efforts of a number of hydraulic laboratories, including the Cooperative Research Project of the Soil Conservation Service and the California Institute of Technology. But even without further laboratory work it is apparent that each one of these factors is taken into account in some way or other in conventional scour-resistant designs for hydraulic structures.

Scour-control factors (1) and (2)--The first two factors, sediment-input and sediment-output capacity determine stream-behavior. For instance, the cross-section, elevation, and slope of the bed and banks of the stream existing before a dam or other structure is erected are changing quantities determined by the accumulated effects of factors (1) and (2) during the history of the stream. Aggradation or degradation may be in progress at the time of observation, depending on which factor predominates.

The influence of factors (1) and (2) is normally recognized in the selection of the elevation or grade of the end of the water-carrying portion of the structure and of the depth of cut-off wall, if any is used. The most common practice is to place the end of the structure at or below some stream-bed elevation that may be presumed to exist for the design conditions, and to protect the structure against local and extreme disturbances of the bed by the use of a cut-off wall extending below the depth of any anticipated scour.

Factors (1) and (2) furnish a stream-channel condition on which the local effects of the other factors are superposed. In each of factors (1) and (2), the influences of flow-characteristics and of bed- and bank-material characteristics along the stream-channel are felt.

Factor (3)--The third factor, the resistance of the bed- and bank-materials to dislodgment and entrainment, affects the rate at which sediment particles may be loosened and mixed into the stream. It is determined by several characteristics of the bed-material. In a single-sized, incoherent, granular material such as a well-sorted sand, gravel, or rip-rap material, the size, weight, shape, orientation and packing of the particles determine their resistance to dislodgment. These characteristics determine settling-velocity and, therefore, resistance to suspending action. But other factors may affect resistance to the dislodgment from the bed- or bank-mass that must precede suspension. Particles lying on sloping faces are easier to dislodge than those on the bottom. Particles lying in well-graded beds are more difficult to dislodge than those in beds of sorted material until the fine grains are washed away and sorted from the coarse. Even then, if the coarse particles are sufficiently large and heavy, the formation of a scour-pavement may prevent the removal of finer materials a short distance below the surface. The most extreme resistance, of course, is offered by particles in cemented or tightly packed masses in which either a tension-transferring agency or resistance to interstitial flow [see 8 of "References" at end of paper] may prevent rapid removal of surface particles.

These inherent characteristics of bed- and bank-materials have been recognized in several ways in scour-resistant design. In the selection of sites and locations for hydraulic structures, arrangements are made to terminate artificial channels, such as spillways, in stream-reaches lined with the most resistant natural material. Outlets have been designed so as to give better protection to weak materials than is given to scour-resistant sediments. Accumulated engineering experience has produced tables of permissible velocities for channels in various materials.

Rip-rap pavings have been laid both for original work and for repair. The advantages of graded or well-interlocked particles in revetments may be predicted from the added scour-resistance of closely packed materials. However, notable failures have taken place when other agencies than surface attack, by disrupting interlocked or cemented pavings, have allowed pot-holes to form, to grow, and to demolish the whole protective work.

Factor (4)--The fourth significant factor in scour-control is the mixing or stirring power of the eddies in the scour-zone. This feature of stream-flow produces sediment-suspending power. Local excess of sediment-suspending ability, and thus of transporting ability, over that existing in normal stream-reaches is the most important factor in localized scour. Recognition of the nature of this factor is owed to the application of modern fluid-mechanics to stream-dynamics. At the present time, in sediment-suspension studies, mixing intensity must be experimentally determined for specific conditions. One of the variables determining the amount of sediment suspended by a given eddy-system is the concentration of sediment available for mixing at the point of loading, that is, the bed.

The ability of the stream to remove sediment in suspension from a given zone depends on the mean velocity of the fluid in which the sediment is suspended and on the opportunity afforded for the settling out of the sediment in zones of low-suspending ability.

A number of distinct types of eddies or mixing systems exist in normal channel-flow and in scour-zones. Each of these is occasionally referred to as "turbulence". Rather than a discussion of the scope of that magic word, a description of the sediment-suspending characteristics of particular eddy-motions will be given. In normal channel-flow, there are regular and irregular three-dimensional motions in addition to the mean motion of flow down the channel. Unless the portions of the stream in which such motions exist are identified by foreign material entrained with the water, air-bubbles or soil-particles, for instance, these eddies are not visible. Special instruments are necessary for indication of the regular motions and the irregular motions are apparent only in fluctuations. These motions, for all the difficulty of observing them, must be recognized as those responsible for the maintenance of sediment in suspension in a stream. They result, primarily, from the friction-stresses set up in the flow passing the bed and banks of a stream. The continued formation of eddies and their subsequent decay is the process of energy-dissipation through which the energy "losses" in channel-flow are converted to heat.

More familiar to hydraulic engineers are the eddies set up by individual obstructions to channel-flow or by sharp, sudden, or violent changes in the flow-outlines. These eddies, and others associated with them, but not so easily observed, are responsible for the greatly increased sediment-suspending ability of stream-flow at points of localized scour. Like the eddies of channel-flow, the strong eddies just described are an essential part of the agency by which "lost" energy is taken from the stream.

Factor (5)--It is difficult to give examples of attempts to control eddy-formation without at the same time discussing the fifth factor, the mean velocity of flow through the scour-zone. The magnitude, direction, and distribution of this velocity are important. If the principal flow attacks the bank or bed and is turned by it, pressure-gradients and shear-stresses are set up that loosen particles and that also develop eddy-motion in the flow to aid in suspending the loosened particles. If the principal flow is intense enough near the bottom it may add to scour by increased drag and bed-load motion. Lastly, the principal flow-rate and direction determine the opportunity for sediment, once suspended, to settle back into the scour-hole, for they determine the time available for settling.

Experimental demonstration--Laboratory experiments initiated by N. A. Christensen and Hunter Rouse and continued by the writer serve to demonstrate the importance of the scour-control factors to a particular scouring situation. In these experiments, a jet was directed vertically downward onto a submerged bed of well-sorted sand. Regardless of the ultimate intensity of the jet, during the first instant of jet-flow, the jet was simply deflected as it would be by a slab of masonry (Fig. 1). In the corner, the velocity-energy of the stream produced a stagnation pressure, tending to hold the sand-grains down. Only through fluctuations and eccentricities of velocity- and pressure-distribution could grains be loosened under this stabilizing force.

Going away from the corner and downstream the pressure-gradient and the high velocities were soon able to move grains along the bed. The suspending action of the eddies resulting from the shock loss at the bend was relatively unimportant. Particles were transported a short distance and deposited close to the corner. But the removal of even a few grains of sand changed the outlines of the flow (Fig. 2).

The jet then entered a rounded pit and had to turn more than 90° in order to leave over the growing dune of deposited material. More intense eddies were produced and still the stream was carrying only a small amount of bed-load. As the pit deepened (Figs. 3 and 4) the face of the dune of deposited material steepened. When the angle of repose (approximately 30°) was exceeded, sliding took place (Fig. 5), the direction of bed-load motion reversed, and suspension became the

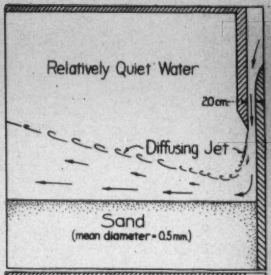


Fig. 1--Form of sand-bed during first instant of jet-flow, time one second after start

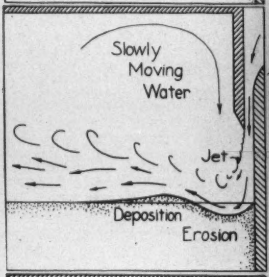
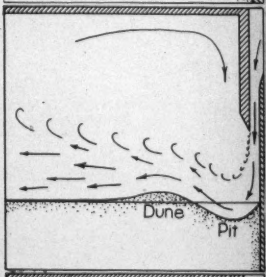


Fig. 2--Scour-pit and deflected jet, time 25 seconds



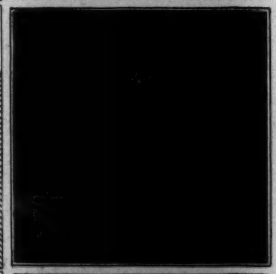


Fig. 3--Growth of scour-pit, time 47 seconds

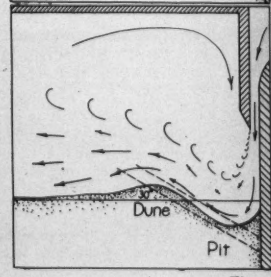


Fig. 4--Scour-pit at maximum size before sliding of dune-face, time 60 seconds

Figs. 1-4--Scour by a submerged jet

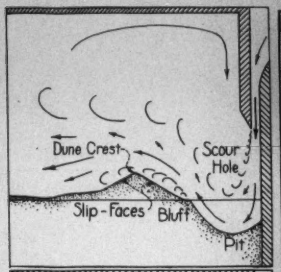


Fig. 5--Formation of slip-faces and loading bluff, time 70 seconds

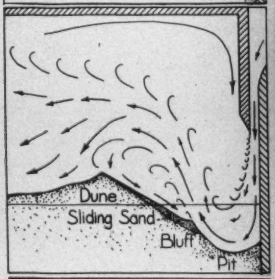
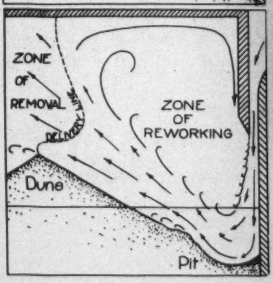


Fig. 6--Fully developed scour-hole pattern (note that suspended sediment, by increasing weight of jet, causes it to flow as a density-current that bends downward as it passes over dune), time 110 seconds



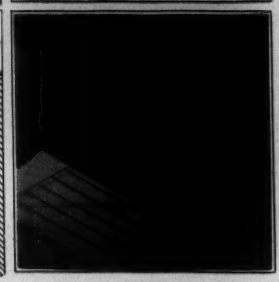


Fig. 7--Advanced stage of scour-hole growth (note increasing distance from loading bluff to crest of dune and thus to delivery-line), time 110 seconds

Figs. 5-7--Scour by a submerged jet

only phase of transportation capable of removing sediment over the dune crest (Figs. 6 and 7). The mixing system holding particles in suspension was composed of the eddies produced in the scour-pit. The rate of growth of the scour-hole became the rate of removal of particles suspended by the eddy-system.

Let us examine the path of particles from the zone of highest concentration to the point of delivery outside the scour-hole. The greatest loading takes place at the bluff or wave-front where sand sliding down the dune-face (Bagnold's "slip-face") intersects the stream. As we proceed downstream from this point, the rate of deposition exceeds the rate of entrainment and the concentration of sediment in suspension decreases steadily. In short, the rate of transportation decreases in the downstream direction. This decrease is rapid and relatively insensitive to the gross size of the scour-hole, but its influence on scour-hole growth is directly related to scour-hole size. As the hole increases in size and more opportunity is afforded for particles to settle out, the concentration of sediment in the stream passing over the top of the dune becomes

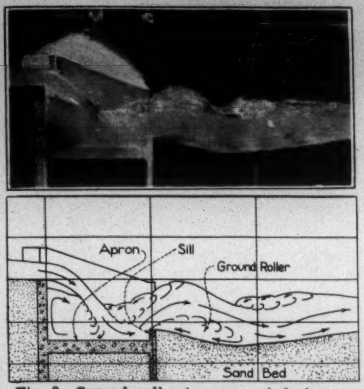


Fig. 8--Ground-roller in a scour-hole (scour-hole shown was formed by laboratory model of gully-control drop-structure; scale is indicated by 0.5-foot spacing of vertical grid-wires)

smaller and smaller. The concentration of sediment in suspension in this zone determines the rate of removal of sediment from the scour-hole. The stream leaving the scour-hole and carrying the sediment with it must spread out and change its direction to the horizontal. In doing so it will drop some of its particles upstream from the dune-crest and some downstream. A curved surface (Fig. 7) extending from the crest to the water-surface separates the zones of deposition inside and outside the scour-hole. Only the sediment carried beyond this boundary is removed from the scour-hole. In the increasing distance from the loading zone to the boundary surface, we find sufficient cause for the rapid decrease in scour-hole growth-rate generally observed with increasing scour-hole size.

The preceding analysis of the significance of eddies, suspension, and settling, to scour leads to a simple description of the effect of introducing sediment into the scouring jet. A few experiments have already shown that, at a given stage of scour-hole growth, the rate of transportation of sediment out of the scour-hole is changed but little by the introduction of particles of the same sediment in the jet. The most important change produced in the action of the jet is the increase in the sediment-concentration at the point of loading. The sediment in the inflow can increase the output of sediment only by the ratio of the input concentration to the concentration at the loading point in the scour-pit. For scour-holes of appreciable depth and size the loading concentration is many times the output concentration. Therefore, if the sediment input is of the same order that the output was during scour by the clear-water jet, the addition of sediment in the jet will increase the output only slightly. From the discussion of scour-control factors (1) and (2) it is seen that scour-hole growth is only excess of sediment output over sediment input. Therefore, depending on excess input or output, the scour-hole may backfill to reach equilibrium (high input) or grow to reach equilibrium (low input).

In general, the shape and rate of growth of scour-holes are primarily matters of eddy-production and of velocities as related to the stability of sediment-particles. For steady flow, the control of maximum scour-hole depth and size is owed to the equilibrium of input and output described above, just as the control of grade and elevation in a normal stream-reach is predominantly a matter of sediment input and output. For rapidly changing conditions, however, the duration and variation of sediment input, sediment output, and stream-flow become important. For instance, in short floods or in laboratory studies, the size of the scour-hole may be limited more by flood-duration than by sediment inflow.

Design-use of factors (4) and (5)--Returning now to the description of the use of the principles of eddy- and velocity-control in the design of hydraulic structures, we find in the problem of spillway-design for overflow dams several conspicuous applications. The ideas of protection against direct impact of falling water and of dissipation of its kinetic energy are firmly established. However, a few laboratory workers have made progress beyond these ideas by making a closer approach to the eddy-control principle.

It is possible to discuss the problem of scour-control below spillways in terms of the use of sills and baffles of various types and for various purposes on spillway-aprons. Observation of spillways in which the flow is led off of a horizontal apron at a relatively high velocity onto an erodible bed has shown the need for protection against undermining of the spillway-apron and its subsequent destruction. These are common phenomena pertaining alike to great dams constructed for power-development, to dams for the canalization of rivers, and to grade-control dams in canals and gullies. One of the most successful procedures for combating undermining has been the use of bottom-anchored obstructions to flow, installed for energy-dissipation and flow-deflection. Each such device, be it continuous sill, dentated sill, interrupted sill, baffle or block, produces both effects. But, as has already been pointed out by many, good flow-deflection characteristics are

not necessarily good energy-dissipation characteristics, and vice versa.

Both flow-deflection and energy-dissipation as accomplished by such devices are phenomena of shock-loss and eddy-production. As such, they have direct and characteristic effects on sediment-suspension and on intensity and distribution of velocity in the region of incipient scour. Separation downstream from transverse sills, baffles, or deflectors, sets up an eddy-system whose regular features are familiarly known as the "ground-roller" (Fig. 8). The scour-control characteristics of a given spillway-design are intimately related to the nature of the flow-pattern and eddy-system produced by the terminal sill of the spillway-bucket or apron.

Even the simple transition from a flat apron to the erodible bed of a stream can develop a ground-roller if a scour-hole is produced at all. In the scour-hole, occupied in part by the ground-roller, the direction of flow along the stream-bed varies from upstream to downstream. A peculiar advantage of the ground-roller type of flow is that it contains an upstream motion that is capable of transporting sediment upstream and thus of preventing destructive undermining of the toe of the apron. This advantage is obtained to various extents by the different obstructions that are placed at the downstream-end of the apron. Scour-holes whose shape is controlled by a stable ground-roller motion grow in much the same fashion as the laboratory scour-hole previously discussed. Once the ground-roller has been established, no change takes place in the shape of the scour-hole; growth is a matter of increase in scale and downstream shift only.

The reasons that so many different types of sill or deflector have been used are: (1) That varying amounts of energy-dissipation have been intended to suit various conditions of downstream flow and sedimentation, and (2) that attempts have been made to reduce the eddy-intensity of the ground-roller system to the minimum required for protection against undermining. Where the maximum attention has been given to energy-dissipation, a very strong ground-roller may be produced with a scour-hole of desirable shape but of greater depth than might be desired. One particular disadvantage of this type of performance, probably related to the intensity of the ground-roller, is the presence of deep scour at the ends of the roller near the banks of the stream.

Interrupted and dentated sills have been tested and used by different individuals and organizations. In each of these devices, some portions of the flow are deflected less than the other portions so that the development of the ground-roller is impaired. From the preceding descripton of the protective action of ground-rollers it should be evident that the upstream direction of flow only, not high upstream velocity, is essential to this process of scour-control. Therefore, any weakening of the ground-roller that is accomplished uniformly enough may decrease the overall eddy-intensity and thus the rate of scour-hole growth and the equilibrium depth of scour. A notable effect of attempts to improve scour-control in this way is reduction in pot-holing near the banks. This finding lends strength to the idea that the eddies that accomplish deep scour near the banks are associated with the ends of the ground-roller.

In some structures the greater part of the energy-dissipating eddy-production takes place near the upstream rather than the downstream-end of the apron. This is particularly true of hydraulic-jump structures in which the tailwater-depth is sufficient to maintain the jump on the apron without the use of auxiliary weirs or baffles. In structures of this type, the terminal sill has primarily the function of flow-deflection or ground-roller control. Therefore, interrupted or dentated, or low, continuous sills have been used with considerable success.

In the discussion of the importance of eddies to scour, most of the attention has been given to irregular motion and to regular or roller motion about horizontal axes transverse to the stream. Less is known about regular vortex motions whose axes are vertical, oblique or horizontal and parallel to the direction of stream-flow. Observation and laboratory study alike indicate that eddies with vertical axes, such as those established near the banks at the end of a spillway, are associated with deep scour. Claims are made for certain types of interrupted sills or baffles, particularly the Rehbock dentated sill, that these devices afford better protection against eccentric velocity-distribution (in plan) and consequent pot-holing from vertical-axis formation than do straight transverse sills. The writer's own experience with longitudinal sills and baffles leads him to believe that the large flat baffle-faces, parallel to the principal stream-flow, of the Rehbock sills may furnish their resistance to cross-flow and to pot-holing. However, the whole matter of the effect of eddies with vertical or oblique axes, or with axes parallel to the stream-flow remains a field for pioneer exploration.

Six scour-control principles-In recognition of his own choice of five significant factors in scour-control the writer wishes to propose six basic principles for procedure in the design of scour-control devices as follows: (1) Take into account the sediment passing through the

structure; (2) reduce the downstream sediment-carrying capacity to a minimum; (3) choose a site with bed and banks of the most stable materials, or increase particle-stability artificially; (4) produce a stable flow-pattern with optimum eddy-orientation and minimum eddy-intensity; (5) reduce flow-velocities to the minimum; and (6) apply each of the first five principles with due regard for the others.

The first five principles have been suggested in direct recognition of the five scour-control factors, respectively. The sixth principle is stated in recognition of the impossibility of applying the preceding five independently. It must be recognized also that one or more of the principles may be inapplicable to a given situation because of inconsistency of that phase of scour-control with the purpose for which the structure is to be built.

The writer has set down certain generalities on scour-control because he believes they may be valuable in directing further research in scour-control, in guiding the location and design of structures, and in analyzing the performance of existing structures. Obviously, the nature of the material he has presented establishes the debt the writer owes to others studying and writing in the field of scour-control. The references cited below have been of particular value to him in formulating his analyses.

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SOME EVIDENCE REGARDING THE KIND AND QUANTITY OF SEDIMENT TRANSPORTED BY DENSITY-CURRENTS

Hugh Stevens Bell

Introduction

Density-currents are of major importance as transporting and sorting agents for fine sediment. Under unusual or extreme conditions they have a part in the distribution of surprisingly coarse material. The magnitude of the work they perform in sedimentation may have been obscured somewhat in recent years because there has been a tendency to think of density-currents

almost solely as turbid underflows in bodies of still water, especially in reservoirs that are fed by muddy rivers. Density-currents are not limited to underflows, be they turbid or otherwise. Their occurrence is confined neither to reservoirs in particular nor to bodies of water in general. For example, dust storms usually are true density-currents [see 1 of "References" at end of paper]. The importance of the atmosphere as a transporting and sorting agent is well known, and has been demonstrated clearly by evidence gathered by JOHAN AUGUST UDDEN [2], EDWARD ELWAY FREE [3], and many others. The fact that needs wider recognition is that the atmospheric transportation of sediment is accomplished very largely by density-currents.

Although some quantitative data are available as to the kind of sediment transported by density-currents, they are too few to justify conclusions other than tentative ones. As to the volume of sediment transported, there is apparently a complete absence of quantitative data, although a large body of excellent qualitative data has been obtained since 1935 by the United States Bureau of Reclamation at Lake Mead [4], and some valuable information has been gathered by the United States Soil Conservation Service at Lake Issaqueena, near Clemson, South Carolina [5]. With these conspicuous exceptions present-day estimates as to the quantity of sediment transported by density-currents must be based upon evidence that is as incomplete, inadequate, indirect and, scientifically, as unsatisfactory as that available to UDDEN nearly a half century ago. Meanwhile, methods of making mechanical analyses of sediments have been simplified and vastly improved [6], and new sampling techniques and instruments have been developed for use in investigating sediment suspended by water [7]. Since FREE pointed out the inadequacies prevalent in 1911, little, if any, progress has been made in the technique or the equipment for accomplishing the much more difficult task of obtaining true samples of sediment suspended in the atmosphere [8].

If the present paper does no more than make evident the need for more and better data, it will have served a worthy purpose.

The Quantity of Sediment Transported by Density-Currents

Data are available upon which to base a reasonably dependable estimate as to the quantity of sediment transported by turbid underflows at Lake Mead since storage began on February 1, 1935. For the first 15 months of storage, water was released through a diversion-tunnel at approximately the normal low-water level of the Colorado River. This discharge normally was clear but at least four times during 1935 it became very muddy although the surface water in the reservoir remained clear. This indicated that turbid underflows were reaching the dam. NATHAN C. GROVER and CHARLES S. HOWARD estimated that as much as 6,000,000 tons of fine sediment, brought by density-currents into lower Lake Mead, was discharged through the tunnel-outlets during the 35 days of turbid outflow in 1935 [9]. Had this sediment remained in the reservoir and reached a concentration of 60 pounds dry weight per cubic foot, it would have occupied 4,600 acre-feet of storage space. Volumetrically this is a conservative estimate. Fine sediment, deposited under water and not subjected to compaction by exposure to the air, may have a concentration of less than 30 pounds per cubic foot.

Since May 1, 1935, withdrawals have been made through towers at levels 250 and 400 feet higher than that of the tunnel-outlet. No turbid water has been discharged and, therefore, all sediment transported by density-currents has been retained within the reservoir where it has formed a submerged lake of mud that extends upstream for approximately 40 miles. It is possible to estimate the quantity of sediment in this lake by using measurements of sediment-concentration and depth obtained by the Bureau of Reclamation in conjunction with data contained in the original capacity-table prepared by the Soil Conservation Service [10]. Calculated upon this basis the mean daily rate of sediment-accumulation in the submerged lake appears to have been about 135,000 tons, or slightly more than 100 acre-feet at 60 pounds per cubic foot, for the period from May 1, 1936, to December 1, 1941. This is approximately seven times the rate of sediment-discharge as calculated by GROVER and HOWARD for 11 months of 1935.

Although density-currents probably play an important part in the transportation of fine sediment whenever muddy streams enter bodies of still water, their activity is not limited to such circumstances. Waves stir up sediment along shores and on sufficiently shallow bottoms during storms, and the suspensions of fine particles created in this manner become density-currents if there are bottom slopes down which they may move. Thus the fine-grained portion of the sediment, because it remains in suspension longer, is carried away into deeper water, but the coarser portion is redeposited very promptly. The coarsest constituents may not be thrown into suspension at all. Usually it is assumed that sorting and transportation can take place under such circumstances only if currents exist at the time the suspensions are created [11]. This view fails to recognize the fact that if a sloping bottom is present, suspensions are very apt to become turbid

underflows. Perhaps seismic disturbances create other suspensions at depths that are never reached by even the most violent storm-waves. It seems entirely possible that the total volume of the sediment transported by aqueous density-currents surpasses that of the sediment carried to the oceans by all the rivers of the world.

Major dust-storms involve from a few hundred to more than a million cubic miles of atmosphere [12]. From evidence UDDEN had available for 32 dust-storms, he calculated that the load of suspended sediment ranged from 160 to 126,000 tons per cubic mile of turbid atmosphere [13]. If the latter figure seems unreasonable it is well to remember that if the suspended particles have a mean density of 2.2 and the sediment-concentration is 1 part per 100,000 by volume, the dust-load will be approximately 100,000 tons per cubic mile.

Such evidence as has been gathered during the present century does not indicate that UDDEN'S estimates should be rejected. A dust-storm that originated west of the Mississippi River passed over Washington, D. C., early in May 1934. Visibility was reduced to half a mile. From data gathered over Washington it was estimated that the dusty air-mass contained approximately 100 tons of sediment per cubic mile [14]. This is equivalent to 20 parts per million (ppm) by weight, but only to 0.01 ppm by volume.

On June 5, 1939, a Japanese dust-storm covered 75,000 acres of valuable farm-land on Hokkaido Island with an inch of fine sediment [15]. Assuming that this fresh deposit had a density in situ of 1.3, it weighed approximately 10,000,000 tons. This would be equal to the total sediment-load from 10,000 cubic miles of atmosphere in which the sediment-concentration was ten times as great as in the Washington storm. It seems probable, therefore, that the concentration was actually very much greater than the suggested value--greater, perhaps, than the highest estimate made by UDDEN.

In March 1918 a storm scattered dust from Iowa to Maine. It was estimated to have deposited 13.5 tons of sediment per square mile at Madison, Wisconsin [16]. On Hokkaido Island the figure was probably not far from 85,000 tons per square mile. In some of the famous falls of sirocco dust in Europe the data indicate deposits of as much as 30 grams per square meter [17]. On Hokkaido it was approximately 30,000 grams per square meter. It is of interest that the Monthly Weather Review comments that the Japanese storm was one "rivaling those of the United States' Dust Bowl" [18].

Baca County, Colorado, lies near the center of an enormous dust-bowl that includes areas in Colorado, Nebraska, Kansas, Oklahoma, Texas, and New Mexico. During 1936 Baca County experienced dust-storms in which pedestrians collided with one another because visibility was reduced to zero. Highway travel was paralyzed, and lighted display-windows were not visible from a distance of 40 feet. Aviators reported dust at altitudes of 15,000 to 20,000 feet [19]. The frequency of dust-storms in that area is shown by the records of the United States Weather Bureau at Amarillo, Texas. Between January 18, 1933, and February 26, 1936, this station recorded 192 such storms. In 24 of these visibility was reduced to less than 500 feet, and in 35 others to less than half a mile. Although seven storms continued for 50 hours or longer, the average duration for the entire series was ten hours.

Since World War I practically all top-soil has been stripped by atmospheric density-currents from several thousand square miles in this particular dust-bowl, and from 25 to 75 per cent has been blown from a much greater area [20]. The total volume removed during the last quarter-century from this and other American dust-bowls will never be known, but it probably should be measured in cubic miles rather than in millions of tons or thousands of acre-feet.

Since the days of the poet HOMER, falls of dust have been recorded in Europe [21]. From meteorological evidence it has been demonstrated that this dust comes from the Sahara, and there is every reason for believing that that great sandy waste is the result of prolonged degradation by wind. The sand that remains is too coarse to be readily transported by atmospheric density-currents. According to FREE, an average of more than 5-1/2 inches of material from the desert has been deposited over much of Europe by dust-storms in the three thousand odd years during which there is authentic historic evidence of their occurrence [22]. This statement has been given wide circulation in scientific literature. By referring to the data submitted as a basis for this estimate, it will be seen that two unfortunate arithmetical errors have resulted in a final figure that is 100-fold too high. FREE'S estimate seems reasonable, and may be a good one; it is not supported, however, by the data he submits.

CHARLES ROLLIN KEYES estimates that 0.01 inch of sediment is deposited annually by dust-

storms along the Missouri River [23], and BOHUMIL SHIMEK gives one mm as the rate of accumulation of Mississippi Valley loess [24]. It will be noted that these rates are roughly five and 20 times as great as FREE'S estimate for sirocco dust in Europe. FREE arrived at a figure of not less than one inch per century as the rate of accumulation of wind-borne dust in the Mississippi Valley [25]. This estimate is based upon the statement that about 0.02 inch was deposited at Rockville, Indiana, during a storm in January 1895. In the light of the known frequent occurrence of dust-storms over the States west of the Mississippi, FREE suggests 0.01 inch as a reasonable estimate of the mean annual deposit. But FREE also states that the dust deposited at Rockville amounted to 1.50 grams per square meter. If it is assumed that the density of this dust was 1.5 (a figure frequently used in Europe for such deposits) then there was one cubic centimeter per square meter. If, however, the deposit was 0.02 inch thick there should have been more than 500 cubic centimeters per square meter, with a total weight of 760 grams. It would seem probable that of the two types of data submitted, those based upon weight would be more acceptable than those based on depth-measurements. Had FREE used the weight, instead of the depth-measurement, and reduced this by 50 per cent as he did the depth-measurement, he would have been forced to conclude that the rate of deposition was such that 50,000 years would be required to produce a deposit one inch thick. In spite of this, the events of the last quarter-century make FREE'S estimate appear to be better than the data submitted to support it.

Evidence of dust-storms of the past is to be had in loess-deposits, the greatest of which are to be found in China where beds occasionally reach a thickness of several hundred feet. The vast loess-deposits that cover tens of thousands of square miles of the Mississippi Valley probably had their origin in the exposed Cretaceous and Tertiary formations found on the High Plains from Wyoming to Texas [26, 27], and in the outwash of recent glacial periods [28].

It is known that "gravity winds" of great violence sweep down from the icy plateaus of Greenland and Antarctica, and that they lose their high velocities and die out rather rapidly as they flow out over the open sea [29]. Such winds owe their comparatively high density to the fact that they are much colder and drier than the atmosphere at the margins of the ice-caps. Unquestionably they are density-currents. It is reasonable to believe that similar winds characterized periods of glaciation in the Mississippi Valley and that they entrained large quantities of rock-flour and other fine debris which were deposited, at no great distance, as loess.

Volcanoes are the greatest single source of atmospheric dust. A fact that is not generally recognized is that the winds that accompany violent volcanic activity often are density-currents that are produced more or less completely by the very sediment they transport. They are, therefore, turbid underflows in the strictest sense. One of PLINY'S letters contains a vivid eye-witness account of the dust-clouds that were produced by Vesuvius when Pompeii was destroyed in 79 A.D. [30].

Various students have estimated that in its eruption of 1815 Tomboro ejected 32, 50, or 92 cubic miles of dust that was scattered over an area of 6,000,000 square miles [31, 32, 33]. This eruption, like that of Krakatao in 1883, produced rather coarse deposits several inches deep at a distance of 1,000 miles [34]. In his report to the Dutch Government on the eruption of Krakatao, R. D. M. VERBEEK estimated that 4.3 cubic miles of material was thrown out, and that about one-third fell at a distance of more than 15 km from the volcano [35]. This dust is said to have settled all over the world. FREE has assembled data on a large number of eruptions in various parts of the world, and cites many instances of volcanic dust being carried by the atmosphere from 100 to 1500 miles and deposited in layers of appreciable thickness [36]. According to estimates by N. S. SHALER, approximately 600 cubic miles of fine material was ejected from the world's volcanoes in the century and a half between 1770 and 1920, and a very large percentage of this was of sizes that could be readily transported by the atmosphere [37].

The evidence that has been presented in the foregoing paragraphs is a fair sample of the kind of information that is available. It is obvious that more basic facts, particularly quantitative data, are needed before the importance of density-currents as transporting agents can be evaluated accurately. There can be no doubt, however, that their role is a major one.

The Kind of Sediment Transported by Density-Currents

UDDEN concluded, after considerable study of windblown dust from many sources and some experimentation, that ordinary strong winds do not transport in suspension readily quartz particles that are larger than 0.1 mm in diameter [38]. According to JOHANNES WALTHER particles about two mm in diameter can be transported by the wind, but not held in suspension, and gravel the size of peas rarely may be carried along [39]. FREE states that R. W. PUMPELLY, GERHARD

Table 1--Mechanical analyses of dustfalls, loess, and bottom-deposits

No.	Clay	Silt		Sand	Remarks
	<5μ	5μ-20μ,	20μ-50μ	>50μ	
	Per cent by weight				
1	24.2	72.6		3.2	Average for samples from five American dustfalls
2	33.4	64.0		2.6	Dustfall, New Hampshire and Vermont, February 24, 1936 [41]
3	25.6	68.4		6.0	Dustfall, Madison, Wisconsin, March 19. 1920 [42]
4	32.0	56.4		11.5	Loess, Grundy County, Missouri [42]
5	24.5	66.5		9.0	Loess, Muscatine County, Iowa [42]
6	10.5	42.3		47.2	Loess, North Platte, Nebraska [42]
7	74.1	23.9	2.0	none	Bottom-deposits, Lake Mead, mean values for 81 samples within 30 miles of Boulder Dam, January 1938 to July 1940; dispersed with sodium oxalate [4]
8	1.3	95.4	3.3	trace	Bottom-deposits, Lake Mead, mean values for 133 samples, as above, but not chemically dispersed [4]
9a	67.0	24.2	8.8	trace	Bottom-deposits, Lake Arthur Reservoir, 3,000 feet from
9b	67.0	27.5	5.5	trace	Dam; original samples contained nine per cent by weight soluble and organic matter [43]
10	77.4	22.6		trace	Sediment discharged through valves, Lake Arthur; sample contained 7 per cent soluble and organic matter [43]
11	78.7	19.3	1.5	0.5	Bottom-deposits, Lake Issaqueena, mean values for three samples within 2200 feet of Dam [5]

ROHLFS, and N. M. PRZHEVALSKII have seen stones from two inches in diameter to as large as the fist blown along in Turkestan, the Sahara and Gobi deserts, respectively [40].

In this paper interest is centered in suspended load. Mechanical analyses indicate that atmospheric currents transport material coarser than that ordinarily carried by aqueous underflows, and that, unless volcanic activity is involved, under all but extreme conditions the sediments transported by density-currents contain little or no material that is more than 0.1 mm in diameter. Almost invariably these sediments are very well sorted.

In a series of samples from five American dust-falls approximately 76 per cent of the sediment was coarser than five microns, and individual samples contained from 2.6 to 6 per cent of sediment coarser than 50 microns (Table 1, Nos. 1, 2, and 3). Loess, apparently, contains a higher percentage of coarser material (Table 1, Nos. 4, 5, and 6). In a series of 81 bottom-samples obtained at Lake Mead within 30 miles of Boulder Dam, only 26 per cent of the sediment was coarser than five microns, and particles coarser than 50 microns were ordinarily not present in individual samples (Table 1, No. 7). Samples were obtained during a period of 30 months extending from January, 1938, to July, 1940, and were dispersed with sodium oxalate before analyses were made.

Although Lake Mead was approximately 100 miles long when the samples were taken, the sediment size-distribution is remarkably like that found at Lake Arthur which is only six miles long (Table 1, Nos. 9 and 10), and at Lake Issaqueena which is less than 1.5 miles long (No. 11). The mean bottom-slope at Lake Mead is five feet per mile, at Lake Arthur it is 15, and at Lake Issaqueena it is nearly 23. Since the coarseness of the sediment that can be transported in suspension is greatly influenced by the velocity of the stream, it might be assumed, therefore, that density-current velocities are essentially the same at the three reservoirs, regardless of the considerable difference in bottom-slopes. Field-observations, however, do not support this assumption but indicate that velocities are highest at Lake Mead, and lowest at Lake Issaqueena.

Sediments transported by density-currents at Lake Mead and Lake Arthur are rather highly flocculated. Because flocculation tends to increase the effective settling-velocity of suspended particles, higher stream-velocities are needed to keep particles of a particular size in suspension when they are flocculated than when they are not. By comparing the data in Table 1, No. 7, with that in No. 8 it will be seen that although approximately 74 per cent of the sediment in lower Lake Mead is actually less than five microns in diameter, flocculation causes nearly 99 per cent of it to settle as if it were more than five microns in diameter.

It is evident, then, that higher density-current velocities are needed to transport the flocculated sediment at Lake Mead than are necessary at Lake Issaqueena where flocculation is negligible. The velocity of a density-current is influenced principally by the bottom-slope, the depth of flow, and the magnitude of the difference in density between the two fluids involved. Very little

is known about the depth of flow at the three reservoirs but it is certain that the density-difference is much greater at both Lake Mead and Lake Arthur than at Lake Issaqueena, and this factor alone may increase velocities sufficiently to offset the effect of flocculation.

Santa Anita Reservoir, in the San Gabriel Mountains, near Arcadia, California, is approximately half a mile in length and has a mean bottom-slope in excess of 300 feet per mile. During the great storm of March 1938 an underflow of sediment and debris reached the dam and succeeded in clogging two outlets that were operating and fully open [44]. One of these outlets is located 21 feet above the other. Before the storm the bottom outlet was 17 feet above the sediment-level. After the storm the top outlet was 17 feet below the sediment-level. The fresh bottom-deposits near the dam were composed of silt, sand, and gravel in which were embedded bits of household equipment that had been in cabins in the canyon above the reservoir prior to the storm. Slopes similar to or greater than that at Santa Anita are not uncommon in the oceans. Wave-action during violent storms, may create suspensions that include rather coarse sand and, on such slopes, these suspensions may flow as density-currents. Evidence that they do is probably already available in the rapidly growing body of data on marine sediments.

Density-currents that result from volcanic activity transport relatively coarse material because of the method of entrainment of the sediment, and because high sediment-concentrations are frequently present on steep slopes. FRANK A. PERRET observed a nuée ardente at Mt. Pelée that had a mean velocity of 96 miles per hour for a distance of four miles [45]. His observations indicate that large blocks of lava may be carried as bed-load on steep slopes.

In 1898 UDDEN published a mechanical analysis of volcanic dust that fell in Norway more than 600 miles from its point of origin in Iceland [46]. Only a fraction of one per cent of this sediment was finer than 16 microns, about ten per cent was coarser than 125 microns, and practically none of it was larger than 250 microns. The almost complete absence of particles finer than 16 microns may indicate that the material had been ejected to heights from which such fine particles were unable to return to Earth in the time required for the sediment-laden air-mass to travel from Iceland to Norway.

Conclusion

Evidence now available shows clearly that both aqueous and atmospheric density-currents can and do transport enormous quantities of fine sediment, but data are not adequate for making other than very rough estimates of the total volume of sediment moved in this manner. Material deposited by density-currents is almost invariably well sorted, and apparently, atmospheric deposits are considerably coarser than aqueous ones.

The need for data like those gathered at Lake Mead is greater than it has ever been. The problems that such information may help to solve are not all academic ones that have to do with the size or the sorting of sediments, or the origin of loess. Density-currents rob one area of its soil, bury crops on others, disrupt the machinery of transportation, and confront the nation with problems in the fields of economics, sociology, and health. Aqueous density-currents distribute sediment that occupies valuable space in reservoirs, lakes, and harbors--space, incidentally, that increases in importance as the nation becomes more and more dependent upon it. For these, and many other reasons, it is desirable to obtain a more thorough knowledge of them.

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REPORT ON STEEP-SLOPE FLOW

John Hedberg

It has been known for a great many years that the flow of water on steep slopes differs in many respects from that on milder slopes. Of the peculiarities the more important are: (1) A different law of resistance; (2) entrainment of air; and (3) roller-waves.

Regarding the first of these I have little to report except that my observations confirm completely the formula obtained by R. EHRENBERGER [see 1 of "References" at end of paper] for the mean velocity of flow in a rectangular channel of planed wood. In foot-second units his formula reads:

$$V = 97\, R^{0.52}\, S^{0.40} \tag{1}$$

where V is average velocity, R is hydraulic radius, and S is the sine of the slope-angle. This formula was based on tests on slopes from 0.153 to 0.707 and depths of flow up to one foot in a channel approximately ten inches wide. My own observations on a channel of similar size indicate that this formula is valid for much flatter slopes than 0.153 but I am not prepared to say what the lower limit of applicability is. At any rate the older CHEZY formula seems to agree closer with measurements than does that of ROBERT MANNING for slopes appreciably steeper than the critical.

Entrainment of air--The volume of air entrained in flowing water is difficult to measure. I have not as yet been able to check EHRENBERGER'S formulas.

$$P_w = 0.43\, R^{-0.05}\, S^{-0.26} \text{ for } S < 0.476 \tag{2}$$

$$P_w = 0.30\, R^{-0.05}\, S^{-0.74} \text{ for } S > 0.476 \tag{3}$$

where P_w = ratio of water to water-air mixture. It should be noted, however, that the channel used to obtain the data for these formulas was 52-1/2 feet long for the flattest slope (0.155) and only 18 feet long for the steepest (0.762). It is quite possible, therefore, that the volume of air entrained had not yet reached its maximum value, especially at the steeper slopes.

Roller-waves--Regarding the interesting phenomena of roller-waves, I would like to submit a formula for maximum wave-height which I think has some merit.

Although the method of attack admits generalization to all shapes of channels, to avoid complexities I am restricting the derivation to broad rectangular channels of sufficient length for the roller-waves to complete their growth. Consider now a fully developed wave as shown in Figure 1.

Using the subscripts 1 and 2 to designate all terms associated with the minimum and maximum depth, respectively, we will use the following symbols:

Q = steady-flow discharge (ft^3/sec)
S = sine of slope-angle
V = average velocity
ω = wave-velocity
y = depth perpendicular to flow (no air)
y' = depth with entrained air
C = Chezy constant
L = length of wave
x = distance from minimum section
b = width of channel
ρ = density
η = ratio of maximum and minimum depth
y_n = normal depth
$K = \left[\frac{5\eta^{3/2}(\eta - 1)}{2(\eta^{5/2} - 1)}\right]^{2/3}$
β = bulking-factor

Ignoring temporarily the bulking-effect of entrained air and superposing upon the system a velocity ω up the plane, we obtain a steady flow for which the continuity equation (4) applies.

$$by_1(\omega - V_1) = by_2(\omega - V_2) \tag{4}$$

Excluding such extreme slopes that the error in calculating pressures hydrostatically in terms of the depths perpendicular to the flow is substantial, we obtain the pressure-momentum balance as in equation (5).

$$(1/2)\,\rho g b y_1^2 + \rho b y_1(\omega - V_1)^2 = (1/2)\,\rho g b y_2^2 + \rho b y_2(\omega - V_2)^2 \tag{5}$$

Making use of the observation of P. FORCHHEIMER [2] that at the top and bottom of the waves the flow conforms to the CHEZY formula, we have

$$V_1 = C y_1^{1/2} S^{1/2} \tag{6}$$

$$V_2 = C y_2^{1/2} S^{1/2} \tag{7}$$

Eliminating V_1, V_2, and ω from these equations and introducing $\eta = (y_2/y_1)$ we get

$$C^2 S/g = (\eta - 1)(\eta^2 - 1)/2\eta(\eta^{1/2} - 1)^2 \tag{8}$$

Equation (8) is important not only as an advance toward obtaining a formula for maximum wave-height but also because it gives a criterion for the beginning of roller-waves. Let η approach the value 1, then the right side of equation (8) approaches the value of 4. So $(C^2S/g) = 4$ is the lowest value this number can have and have roller-waves exist. That this is exactly the same criterion as obtained by H. JEFFREYS [3] and H. A. THOMAS [4] by completely different

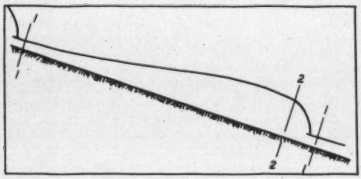

Fig. 1

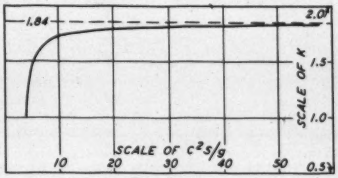

Fig. 2

methods indicates that our procedure is correct so far. I might add that I have tried to obtain an experimental check for this criterion but the shortness of the experimental channel (39 feet) and the ever-present diamond wave-pattern made it difficult to be sure when the initiation began. The lowest observed value for which the roller-waves were unmistakable was $(C^2S/g) = 11$. I hope to improve on this in the near future.

To proceed with the derivation, we observe that the unsteady flow represented by the roller-waves must have an average value equal to the steady flow-discharge. Therefore

$$Q = (1/L) \int_0^L byV dx \tag{9}$$

It is now necessary to make some approximations. The first is that the depth increases uniformly from y_1 to y_2. So

$$dx = [L/(y_2 - y_1)]\, dy \tag{10}$$

Since V_1 and V_2 conform to the CHEZY formula, it is reasonable to assume that the velocities in between will not differ much from this formula. Let us take

$$V = C y^{1/2} S^{1/2} \tag{11}$$

Making these substitutions and carrying out the integration (9), we get finally

$$y_2 = \left[\frac{5Q\eta^{3/2}(\eta - 1)}{2bCS^{1/2}(\eta^{5/2} - 1)} \right]^{2/3} \tag{12}$$

Introducing the normal depth

$$y_n = (Q/bCS^{1/2})^{2/3} \tag{13}$$

we get

$$y_2 = y_n \left[5\eta^{3/2}(\eta - 1)/2(\eta^{5/2} - 1) \right]^{2/3} \tag{14}$$

Using the symbol K to represent the bracketed term we have

$$y_2 = Ky_n \tag{15}$$

The ratio η is easily eliminated if for assumed values of η we calculate (C^2S/g) from (8) and K from the above definition. Then by plotting corresponding values of (C^2S/g) and K, we obtain the curve of Figure 2.

It is now necessary to deal with the entrained air. While it is possible that the insufflation of bubbles of air into the water may effect the resistance in some way, there is no doubt that the general effect is to bulk the flow, especially near the wave-front. Using equation (2), the bulking-factor

$$\beta = (1/P_w) = 2.32\ R^{0.05}\ S^{0.26} \tag{16}$$

The final equation for maximum wave-height is therefore

$$y_2' = \beta y_2 \tag{17}$$

In order to check the validity of (17), the profiles of a number of flows in a 9-inch width, 39-foot redwood channel on a slope S = 0.261 were obtained. It was found, however, that only for very small flows did the channel have sufficient length for the waves to build up to their ultimate size. For one of these the following data were obtained: Q = 0.0393 ft^3/sec, b = 0.75 ft, y_n = 0.0116 ft, S = 0.261, C = 82. So (C^2S/g) = 54.5 and Figure 2 gives K = 1.83. y_2 = 1.83 (0.0116) = 0.0212 ft. Using y_2 for R in (16) we get β = 2.32 (0.824) (0.707) = 1.35. So y_2' = 1.35 (0.0212) = 0.0286 ft.

The measured value of y_2' was 0.0314 foot, which is not a bad check considering the uncertainties of the quantity and distribution of the entrained air.

Concluding remarks--It is hardly necessary to say that there remains a great deal of work to be done before the eccentricities of steep slope-flow are completely clarified. Certainly the formulas for maximum wave-height as given in this paper require further experimental checks before being accepted. Since it is difficult to obtain an adequate range of observation in any one laboratory, I hope that those who have data on the problem will try to check them and let me know the result. The same can be said for the EHRENBERGER formulas for entrained air upon which my own formulas hinge.

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EVAPORATION AND CONSUMPTIVE USE OF WATER EMPIRICAL FORMULAS

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Introduction--As evaporation and transpiration are important elements in the water-cycle, they must be given careful consideration before the available water-resources of a drainage-basin can be satisfactorily ascertained. Evapo-transpiration or consumptive use of water involves problems of water-supply, both surface and underground. This subject is increasingly significant, particularly in the irrigated regions of the West, where consumptive use may be several times as great as precipitation. The consumptive-use requirement for water has become an important factor in the arbitration of controversies over major stream-systems where the public welfare of valleys, states and even nations is involved [see 1 of "References" at end of paper].

In water-supply and irrigation investigations, engineers are called upon to make, within a limited time, estimates of probable past and future evaporation- and transpiration-losses from

areas in river valleys when few long-period hydrologic records, except climatological data, are available. In connection with water-utilization studies made by the Division of Irrigation of the Soil Conservation Service for the National Resources Planning Board [2], the authors were confronted with the problem of determining the past, present, and normal consumptive use of water in valley-areas extending some 500 miles along the Pecos River in New Mexico and Texas. In the limited time available, several methods previously used in the Rio Grande Joint Investigation [1] were employed. The most satisfactory method proved to be the integration-method [1], which depends upon setting up proper unit annual values for evaporation and consumptive use of water for various types of vegetation in different valley-areas. As a part of the Pecos River Investigation a study was made of the relation of evaporation to evapo-transpiration and to humidity and temperature, with the view of developing empirical formulas for estimating unit annual values of current and normal evaporation and consumptive use of water in river valley-areas where records of temperature and humidity are available.

Historical review--The effect of sunshine and heat in stimulating transpiration was studied as early as 1691, according to a review of the literature by ABBE [3]. Measurements of transpiration of various kinds of plants by BRIGGS and SHANTZ indicate a close correlation between transpiration and evaporation from free-water surfaces, air-temperature, solar radiation, and wet-bulb depression readings [4].

Many formulas have been developed in the past for determining evaporation from meteorological observations. For the most part these are based on daily or short-period observations, which are not available for many localities, and are of little practical use by engineers confronted with the problem of estimating average annual evaporation for areas where no evaporation-pan records are available. CUMMINGS and RICHARDSON have made use of the conservation-of-energy principle in determining evaporation [5]. Formulas for estimating consumptive use are not so numerous. THORNTHWAITE and HOLZMAN have developed a method to determine evaporation and transpiration by observing the vapor-pressure gradient between two different levels in the atmosphere [6].

For many years irrigation engineers have used temperature data in estimating consumptive use of water in arid and semiarid areas of the West [7]. HEDKE developed the effective heat method on the Rio Grande [8]. LOWRY and JOHNSON have recently developed a method based on the relation of observed consumptive use to maximum temperature above 32° F during the growing season for average water-supply and crop-conditions [9].

The adaptability of the evaporation-pan as an index for estimating evapo-transpiration losses from moist areas was demonstrated by studies in 1931 [10]. For tules growing in a large tank within the confines of a swamp area at Victorville, California, the percentage of consumptive use with reference to evaporation from a nearby exposed Weather Bureau pan was 95 per cent. Evaporation from pans was used as an index of consumptive use of water on the Rio Grande in 1936, when evaporation-stations were established in valleys extending some 600 miles along the river [1]. A similar procedure has been recommended by the National Resources Planning Board [11]. REEVE and FURR used the evaporation from a shallow black-pan evaporimeter as an index of use of water by mature citrus trees [12].

A review of literature by YOUNG and BLANEY [13] indicates that the use of water by native vegetation having access to an ample ground-water supply may be considerably greater than precipitation in semiarid regions.

Pecos River Investigation--As a part of the Pecos River Joint Investigation [2], evaporation and evapo-transpiration stations were established in different sections of the Pecos River Basin for the purpose of determining unit-evaporation and consumptive use by native ground-water vegetation and for correlating the relationship between evaporation, evapo-transpiration, temperature, and humidity. The key station for evapo-transpiration measurements was located at Carlsbad, New Mexico.

Meteorological conditions influencing evaporation from water-surfaces likewise affect evaporation from soils and transpiration from vegetation. Both evaporation and transpiration freely respond to changes in temperature, wind-movement, and humidity, so that evaporation from water may, under certain conditions, be used as an index of evapo-transpiration losses for areas in which there is ample water to take care of evaporation and transpiration.

Long-period records of evaporation, temperature, and humidity are available for a few sections of the Pecos River Basin and adjacent watersheds. These data, together with the records

published by the Texas Agricultural Experiment Station [14], were used to develop a tentative empirical formula for computing evaporation from a lake surface, where temperature and humidity data are available.

The relation between temperature, humidity, and evaporation was found by plotting average annual observed data for some 15 stations having records varying from 14 to 24 years [14]. This was accomplished by using the average annual per cent of relative humidity as ordinates and the average evaporation per degree of mean temperature as abscissas. Then an equation of a straight line drawn through the mean of the plotted points was developed as

$$E_L = 0.0167\ T(114 - H) \qquad (1)$$

in which E_L = annual lake evaporation in inches (or 0.70 × observed Weather Bureau pan [15] evaporation); T = annual mean temperature in °F; and H = annual average relative humidity in per cent. This tentative equation proved useful in making preliminary estimates of evaporation-losses from free-water surfaces in the Pecos River Basin, where records of temperature and humidity were available.

The next step was to introduce a factor of evaporative force (or heat) which was obtained by multiplying the mean monthly temperature in degrees Fahrenheit by the monthly per cent of annual daytime hours for corresponding months. The per cent of daytime hours varies with the month and latitude [16]. A further study indicated a relation between evaporation and mean temperature, percentage of daytime hours and average relative humidity.

Consideration of these results leads to the monthly empirical formula:

$$e = k\ (tp)\ (114 - h) = kf\ (114 - h) \qquad (2)$$

in which e = monthly evaporation in inches; k = monthly coefficient (varies with the type of pan or water surface); t = mean monthly temperature in °F; p = monthly per cent of annual daytime hours; f = tp = monthly evaporative force (heat-factor); and h = average monthly per cent of relative humidity.

Later analyses--After the Pecos River report [2] had been completed, further analyses were made of available data on evaporation from pans, evapo-transpiration, temperature, daytime hours, and humidity with the view of developing seasonal and annual coefficients for formulas which would be useful to engineers in making estimates of evaporation and consumptive use of water in future water-supply investigations.

Table 1--Observed average monthly evaporation, consumptive use, temperature, and humidity, and calculated monthly consumptive-use index (c), Carlsbad, New Mexico, 1940

Month	Evaporation, inches		Consumptive use, inches	t (See[3])	h (See[3])	p (See[3])	c (See[3])
	U.S.Weather Bureau pan	Bare soil[1]	Sacaton[1]				
January	3.43	[2]1.15	[2]0.89	37	57	7.20	152
February	5.17	[2]1.73	[2]1.34	53	50	7.17	243
March	8.56	2.87	2.22	56	44	8.27	324
April	10.20	3.25	4.48	64	39	8.65	416
May	10.25	4.14	6.42	71	51	9.63	431
June	10.09	3.35	5.79	75	56	9.60	418
July	11.42	3.26	8.07	80	51	9.77	493
August	10.61	4.23	7.09	77	57	9.28	408
September	9.58	2.85	6.13	74	54	8.34	370
October	7.17	2.32	3.50	63	59	7.93	275
November	3.27	1.65	1.80	50	61	7.11	189
December	2.89	1.07	0.37	48	61	7.05	179
Annual	92.64	31.87	48.10	62.3	53.3	100.00	3,898

[1]In sunken tank, water-table at two feet. [2]Interpolated from evaporation record.

[3]t = mean month temperature, °F; h = average monthly relative humidity, per cent; p = per cent of daytime hours of year for month, latitude 32° north (16); f = t × p = evaporative force; c = consumptive-use index = f (114 - h).

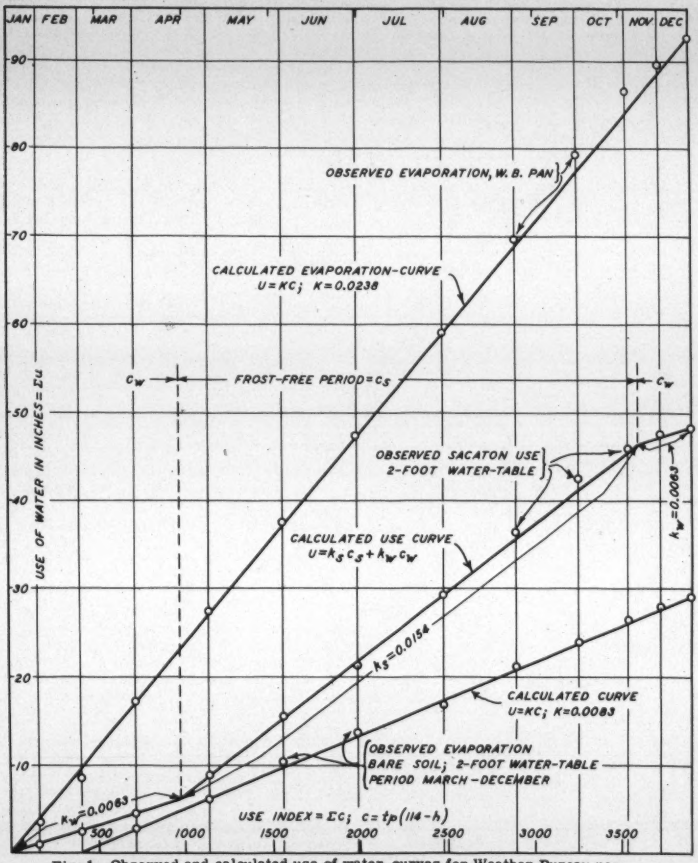

Fig. 1--Observed and calculated use of water-curves for Weather Bureau pan, bare-soil tank, and Sacaton tank, Carlsbad, New Mexico, 1940

A special study was made of data obtained during 1940 at the Evapo-transpiration Station at Carlsbad, New Mexico, on evaporation, temperature, humidity, and precipitation; and on consumptive use of water by salt-grass, sacaton, tules, and salt-cedar (tamarisk) grown in tanks placed in surroundings of natural growth. Some of the data obtained at the Carlsbad Station are shown in Table 1. From equation (2), the general monthly use formula

$$u = kc \qquad (3)$$

is developed, where u = monthly use of water (evaporation or consumptive use) in inches; k = monthly coefficient; and c = f (114 - h) = monthly use index. The value of k is determined from

measured use and varies with the type of water-surface and vegetation. The use index c represents factors of temperature, daytime hours, and humidity. Other factors, influencing use of water, such as wind-movement and barometric pressure, may be reflected in establishing values of k covering a sufficient range of average conditions.

It was found in the Pecos River Area that the annual-use coefficient $K = 1.03 (k_1 + k_2 + \ldots\ldots + k_{12})/12$ approximately, and that the annual-use index $C = c_1 + c_2 \ldots\ldots c_{12}$. Then the annual-use formula may be written as

$$U = KC = \text{annual use (evaporation or consumptive use) in inches} \qquad (4)$$

Equation (4) may be adapted for computing consumptive use for areas in which ample water is available to take care of consumptive water-requirement, by dividing the annual use U into two parts; growing (summer) season use, u_s, and winter period use, u_w. Then without appreciable error

$$U = u_s + u_w = k_s f_s (114 - h_s) + k_w f_w (114 - h_w) = k_s c_s + k_w c_w \qquad (5)$$

in which the subscripts "s" denote growing (summer) season and "w", winter period. The growing season for native ground-water vegetation may be determined approximately from the records of killing frost kept by the Weather Bureau.

The values c, c_s, and c_w may be computed for any location where the latitude, monthly temperature, and humidity are known. The coefficients k, k_s, and k_w may be computed where data on consumptive use are available. They will vary with the type of vegetation. Monthly and annual coefficients for computing evaporation may also be determined from evaporation-pan records.

The seasonal coefficient, k_s and k_w, for Sacaton are developed for Carlsbad, New Mexico, as from the data shown in Table 1 to illustrate the formula $U = k_s c_s + k_w c_w$ as follows:

The observed use of water by Sacaton was 37.00 inches for the approximate growing-period, May 1 to November 1, 1940. The consumptive-use index c_s for this period is equal to the sum of the monthly indexes or $c_s = 431 + 418 + 493 + 408 + 370 + 275 = 2395$. Substituting these values in equation $u_s = k_s c_s$, the value $k_s = u_s/c_s = 37.00/2395 = 0.0154$. In a similar manner the winter coefficient k_w is computed from the observed data for the months of March, November, and December to be $k_w = 0.0063$. Then equation (5) becomes $U = 0.0154\ c_s + 0.0063\ c_w$.

For annual evaporation from water and soil, the value of K in the equation (4) is computed as follows: The observed annual evaporation U at Carlsbad from a Weather Bureau land-pan during 1940 (see Table 1) was 92.64 inches. The value of C, as computed from observed temperature and humidity and calculated evaporative-force, is 3898. Substituting values of U and C in equation (4), K = 0.0238 and the formula (4) becomes U = 0.0238 C. In a like manner a coefficient is computed for evaporation from soil in tank with the water-table at two feet below the ground-surface, as K = 0.0083 and the formula (4) becomes U = 0.0083 C.

Figure 1 has been prepared for the purpose of illustrating these formulas and comparing the calculated use of water with the observed evaporation and consumptive use at the Carlsbad Station. This station was chosen because no other complete data on evaporation from moist soil and consumptive use of water by native vegetation are available in the Pecos River Area. In the chart the summation or accumulative use of water, u, is the ordinate and the accumulative use index c is the abscissa. A study of Figure 1 indicates that these formulas may be useful in estimating annual use of water when a few monthly measurements are missing, but monthly temperature and humidity data are available for the entire year.

The authors have calculated values of K and C for many stations in New Mexico and Texas where records by evaporation-pan and of temperature and humidity are obtainable, with the view of setting up coefficients for estimating normal annual evaporation in other locations where only temperature and humidity data are available. It was found that $C = 1.03\ T\ (114 - H)$ approximately for latitudes 30° to 40° north. In Table 2 are shown annual data for several stations in Texas and New Mexico. A comparison is also made of observed pan-evaporation with calculated evaporation by means of formula U = KC.

The annual-use indexes, C, shown in Table 2, for stations having long-period records are computed from the approximate equation $C = 1.03\ T(114 - H)$, while the annual indexes for records of 1940 are equal to the sum of the monthly use indexes ($C = \Sigma c$), where $c = tp(114 - h)$.

Table 2--Annual observed temperature, humidity, and evaporation, and calculated annual-use index (C), coefficient (K), and evaporation at some stations in Texas and New Mexico

Station	Number of years records	Mean temperature, °F	Average relative humidity, per cent	Observed evaporation, inches	Annual-use index (C)	Calculated annual coefficient (K)	Calculated evaporation, inches[1]	Ratio calculated evaporation to observed evaporation
Sunken type evaporation-pan, 6-feet in diameter								
Texas								
Balmorhea	14	64.0	57.1	70.59	3750	0.0188	75.0	1.06
Chillicothe	21	62.2	61.3	66.63	3378	.0197	67.6	1.01
Nacogdoches	18	66.3	81.7	44.51	2206	.0202	44.1	.99
Temple	18	66.7	72.4	59.15	2858	.0207	57.2	.97
Troup	18	65.9	74.6	52.45	2675	.0196	53.5	1.02
San Antonio	24	69.1	68.0	65.74	3280	.0200	65.6	1.00
Weather Bureau pan, 4-feet in diameter								
New Mexico								
State College	21	60.0	46.7	90.96	4159	.0219	97.3	1.07
Elephant Butte Dam	19	59.6	49.0	96.56	3990	.0241	93.4	.97
Conchas Dam	(1940)	58.6	50.3	[2]103.60	4065	.0255	95.1	.92
State College	(1940)	59.8	52.4	87.97	3897	.0226	91.2	1.04
Carlsbad	(1940)	62.3	53.3	92.64	3898	.0238	91.2	.98
Texas								
Grandfalls	(1940)	63.5	49.8	96.93	4160	.0233	97.3	1.00

[1]Computed by formula U = KC, where K = 0.0200 for sunken pan, six-feet in diameter, and K = 0.0234 for Weather Bureau pan.

[2]Evaporation high, as pan-exposure greater than average station.

From the values of K, shown in Table 2 and those computed for many other areas, tentative normal annual coefficients are derived for estimating evaporation in southern New Mexico and Texas as follows: For sunken type pan, K = 0.0200; for Weather Bureau type pan, K = 0.0234; and for lake-surface, K = 0.0164. (The factor 0.70, which has been generally adopted by engineers [15], is used in reducing the Weather Bureau pan-evaporation to lake-surface evaporation in derivation of the coefficient 0.0164.) In estimating normal annual evaporation where temperature and humidity records are available, the proper coefficients may be substituted in the general formula U = KC. This has been done for some stations and the results are shown in Table 2 for the two types of evaporation-pans in Texas and New Mexico.

Computed coefficients for winter and summer consumptive use of water for native vegetation growing along the Pecos River, based on measurements of evapo-transpiration, temperature, and humidity at Carlsbad, New Mexico, for the year 1940, are as follows: Sacaton, with water-table at four feet, $k_w = 0.0044$ and $k_s = 0.0139$; sacaton, with water-table at two feet, $k_w = 0.0063$ and $k_s = 0.0154$; and salt-cedar (tamarisk), with water-table at two feet, $k_w = 0.0075$ and $k_s = 0.0216$. From observed data in New Mexico the seasonal coefficients for alfalfa growing in areas of high water-table are estimated to be $k_w = 0.0040$ and $k_s = 0.0140$. These are tentative coefficients based on one year's record.

Table 3 has been compiled for the purpose of illustrating how the formula $U = (k_s c_s + k_w c_w)$ may be used in estimating consumptive use of water by ground-water vegetation throughout a basin when records of humidity and temperature are available in different parts of the basin and data on evapo-transpiration, temperature, and humidity are complete at one key station. The coefficients (k_s and k_w), used in the formula $U = (k_s c_s + k_w c_w)$, are computed from measured data for evapo-transpiration, humidity, and temperature at the key station at Carlsbad, as previously described.

Summary and conclusions--In investigations of water-supply and irrigation, engineers are frequently confronted with the problem of estimating the probable past and future evaporation and consumptive use of water in river valley-areas when few long-period records, except climatological data, are available. With this in mind, the paper describes empirical formulas developed, in

Table 3--Estimated summer, winter, and annual consumptive use of water by ground-water vegetation at several locations in the Pecos River Basin, New Mexico and Texas, for 1940[1]

Location	Mean temperature, °F	Average relative humidity	Use index		Consumptive use in inches (see footnote 4)					
					Salt cedar[2]			Sacaton[3]		
			c_s	c_w	u_s	u_w	U	u_s	u_w	U
Las Vegas	50.0	46.6	2,241	1,235	48.4	9.3	57.7	31.1	5.4	36.5
Carlsbad	62.3	53.3	2,623	1,275	56.7	9.7	66.4	36.5	5.6	42.1
Ft. Stockton	63.8	54.2	2,706	1,233	58.4	9.2	67.6	37.6	5.4	43.0
Grandfalls	63.5	49.8	3,157	1,003	68.2	7.5	75.7	43.9	4.4	48.3

[1]Computed by formula $U = (u_s + u_w) = (k_s c_s + k_w c_w)$ and from measured consumptive use of water at Carlsbad, New Mexico. [2]Growing along river with water-table at two feet ($k_s = 0.0216$ and $k_w = 0.0075$). [3]Growing adjacent to river and in moist areas with water-table at four feet ($k_s = 0.0139$ and $k_w = 0.0044$). [4]c_s = growing-season consumptive use index; c_w = winter-period consumptive use index; u_s = growing-season consumptive use of water; u_w = winter-period consumptive use of water; U = annual consumptive use of water.

connection with the Pecos River Joint Investigation, for estimating unit annual values of evaporation from free-water surfaces and consumptive use by native ground-water vegetation when records of temperature, daytime, and humidity are available. The formulas are developed for areas in which there is ample water to take care of evaporation and transpiration.

The evaporation-formula may be used to estimate annual evaporation when a few monthly evaporation-pan records may be missing, but monthly temperature and humidity data are available for the entire year.

The consumptive-use formula is best adapted to native ground-water vegetation but may be used in estimating consumptive use by irrigated crops having access to an ample water-supply, such as alfalfa, when some experimental evapo-transpiration data are available for the crop, together with records of evaporation, temperature, and humidity.

These formulas may be used to estimate the average use of water by evaporation and vegetation within the limits of temperature, humidity, and evaporation from which the formulas were evolved. It should not be inferred from the paper that the formulas can be universally applied. Coefficients should be developed for different climatic conditions in other regions from long-period climatological and evaporation data.

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DISCUSSION

DONALD M. BAKER (Consulting Engineer, Los Angeles, California)--Determination of evaporation and of consumptive use or evapo-transpiration (these last two terms, coined by Western engineers and considered by them as synonymous) frequently presents a difficult problem to engineers making studies of water-supply and utilization. Until physicists develop a procedure whereby the constants in the numerous equations which they propose can be determined by engineers more readily and economically than observations from various types of pans can be secured and translated into terms of open-water-surface evaporation and consumptive use from large areas, primary dependence from the standpoint of economy and time alone will have to be placed upon the pan-observation method and results derived therefrom. Furthermore, until basic data as to evaporation and consumptive use become more numerous than present data relative to temperature, relative humidity, precipitation, and other meteorological phenomena, a large proportion of studies concerning water-supply will of necessity, because of reasons of time and economy, have to depend upon formulas such as developed by the authors, with constants being supplied from available basic data and relationships between observed or derived results for pan-evaporation on the one hand and open-water-surface evaporation and consumptive use on the other.

The formulas proposed by the writers involve the use of the two most important factors which influence evaporation, energy (temperature and length of daytime hours) and relative humidity, data relative to these factors in a given locality usually being available in reasonable amount. Other factors, wind-movement and barometric pressure, of considerably less importance, do not appear in the formulas but were considered as being fairly constant over the entire area in which the investigations were made.

Application of the formulas to other localities might require an evaluation of the effect upon evaporation of barometric pressure (which could probably be expressed in terms of elevation above sea-level) and wind-movement, and the inclusion of these factors in the formulas. Whether this could be satisfactorily accomplished from a further analysis of the data collected by the authors in these experiments is not known, since the magnitude of the variation of barometric pressure and wind-movement within the region in which the observations were made may be too small to develop corrections for these factors. Further study of this subject, over an area where variations in elevation and wind-movement were of considerably greater magnitude should afford an opportunity to evaluate their effect and to allow the inclusion in the formulas of terms which would account for it. It is hoped that this can be accomplished.

From the material presented in the paper, a high correlation between observed and derived results appears to have been achieved. Studies of water-supply involve the use of basic data which in itself is not of an extremely high degree of accuracy, and likewise the making of many assumptions as to past, present, and future conditions, trends and relationships which call for the exercise of a great amount of judgment. The result of such a study cannot therefore be considered to be something having a high degree of precision, but lack of precision can always be remedied in a water-supply study, as in other engineering calculations, by the adoption of a proper safety-factor dependent upon the quality and quantity of basic data available. It is in the selection of this safety-factor that the highest degree of engineering judgment is required.

THE EFFECT OF WALL-FRICTION ON GRAVITY-WAVES

Morrough P. O'Brien and A. D. Chaffin, Jr.

Two-dimensional waves on a free-water surface have been investigated experimentally in relatively narrow laboratory channels. In planning such experiments, there arises a question as to the width necessary to avoid appreciable losses of wave-energy by wall-friction. If the crest-lengths were infinite, as assumed in the theoretical analysis of gravity-waves [H. LAMB, Hydrodynamics, 6th Ed., p. 619], only internal and bottom friction decrease the wave-energy and these effects are usually small but in laboratory wave-tanks friction resulting from the very steep velocity-gradients near the walls of the tank may have an effect so great as to render the experimental results worthless. The practical problem involved is the selection of a width of tank showing inappreciable wall-effect rather than prediction of the loss of energy in a tank of insufficient width.

Analysis of the problem assumes that the motion at each point on the wall may be treated as that of a portion of a flat plate oscillated parallel to itself in contact with a semi-infinite fluid. The velocities used at each point are those obtained from the theory of gravity-waves on the surface of a frictionless liquid, and it is assumed that the wall-friction has no other effect than to reduce wave-heights and energies.

Periodic motion of a solid boundary

Analysis [H. LAMB, loc. cit.] of the steady, periodic motion of an infinite plate oscillating parallel to itself and in contact with a semi-infinite fluid shows that the velocity of the fluid is

$$u = \bar{u} e^{-\sqrt{n/2\nu}\cdot y} \cos(nt - \sqrt{n/2\nu}\cdot y) \qquad (1)$$

Here, u is the velocity parallel to the plate at distance y from it and $\bar{u}$ is the maximum velocity of plate oscillation. The motion dies away rapidly. For example, if the maximum velocity is 1.1 ft/sec, the period 1.15 sec, and the kinematic viscosity 1.08×10^{-5} ft^2 free, the maximum velocity is reduced to 0.1 ft/sec at 0.005 ft from the plate.

The instantaneous tractive force on the plate is

$$\mu \left(\frac{\partial u}{\partial y}\right)_{y=0}$$

and the instantaneous rate of doing work at the surface of the plate is

$$\left[u \cdot \mu \frac{\partial u}{\partial y}\right]_{y=0}$$

The total energy supplied to the fluid and dissipated during one cycle per unit area is

$$D = \mu \int_0^T \left[u \frac{\partial u}{\partial y}\right]_{y=0} dt \qquad (2)$$

Substituting equation (1) and integrating yields

$$D = (\rho \bar{u}^2/2)\sqrt{\pi \nu T} \qquad (3)$$

RAYLEIGH [Scientific Papers 2, p. 239] and SCHLICHTING [Physikal. Zs., v. 33, p. 327, 1932; see S. Goldstein, Modern developments in fluid dynamics, Oxford University Press, 1938, p. 187] analyzed the details of the motion for long, standing waves and found currents perpendicular to and along the stationary boundary superimposed on the wave-motion which would exist in an infinite fluid. These second-order effects are neglected in computing the effect of wall-friction in this paper.

Gravity-waves

Taking the origin of coordinates at the intersection of the still-water surface and one wall with x measured in the direction of wave-motion, z downward and y out from the wall, the theory of frictionless waves to a first approximation yields as the maximum velocities at any depth z,

$$\bar{u}_z = \pm (\pi h/T) \left\{ \cosh [2\pi/L] (d - z)/\sinh [2\pi d/L] \right\} \quad (4)$$

$$\bar{w}_z = \pm (\pi h/T) \left\{ \sinh [2\pi/L] (d - z)/\sinh [2\pi d/L] \right\} \quad (5)$$

The vertical component of velocity becomes zero at the bottom of the channel where z = d but the horizontal component is not identically zero there, although it may be very small if the depth is large as compared to the wave-length.

Neglecting the small region near the intersection of bottom and sides where the friction-effects interfere, the preceding equations may be combined to give the velocities at points influenced by the side walls as

$v = 0$, where $\nu = Nu$

$$u = \left(\frac{\pi h}{T}\right) \frac{\cosh [2\pi/L] (d - z)}{\sinh [2\pi d/L]} \sin 2 (x/L - t/T) \left\{ 1 - e^{-\sqrt{n/2\nu} \cdot y} \sin (nt - \sqrt{n/2\nu} \cdot y) \right\} \quad (6)$$

$$w = \left(\frac{\pi h}{T}\right) \frac{\sinh [2\pi/L] (d - z)}{\sinh [2\pi d/L]} \cos 2 (x/L - t/T) \left\{ 1 - e^{-\sqrt{n/2\nu} \cdot y} \cos (nt - \sqrt{n/2\nu} \cdot y) \right\} \quad (7)$$

The same equation applies to points influenced by the bottom but with z replacing y as the distance out from the solid boundary.

The summation of kinetic and potential energy in one wave-length depends upon the surface-profile. There is some disagreement as to the theoretical form and measurements do not agree exactly with any of the theories but to the accuracy required here the form may be taken as trochoidal and the energy and power computed from the trochoidal theory as equations (8) to (11).

$$E = (wLh^2/8) [1 - M (h^2/L^2)] \quad (8)$$

$$P_0 = C_g E/L \quad (9)$$

$$C_g = C - L (dC/dL) \quad (10)$$

$$C = \sqrt{(gL/2\pi) \tanh (2\pi d/L)} \quad (11)$$

Dissipation of energy

The total dissipation of energy through viscous action would be obtained by integrating throughout the volume of the channel the following function:

$$\phi = \mu \left[2\left(\frac{\partial u}{\partial x}\right)^2 + 2\left(\frac{\partial v}{\partial y}\right)^2 + 2\left(\frac{\partial w}{\partial z}\right)^2 + \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}\right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 \right] \quad (12)$$

Remembering that the normal velocity is zero at all surfaces and that from continuity

$$\frac{\partial v}{\partial y} = -\left(\frac{\partial u}{\partial x} + \frac{\partial w}{\partial y}\right)$$

Equations (6) and (7) may be used to obtain the comparative magnitudes of the averages over one full cycle of the squares of these derivatives at y = 0. The results of this analysis is that $\left(\overline{\frac{\partial u}{\partial y}}\right)^2$ and $\left(\overline{\frac{\partial w}{\partial y}}\right)^2$ are very large as compared with the other quantities along the walls and that $\left(\overline{\frac{\partial u}{\partial z}}\right)^2$ is large at the bottom. The simplified dissipation-function is then

$$\phi_{walls} = \mu \left[\left(\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial y}\right)^2 \right]$$

$$\phi_{bottom} = \mu \left(\frac{\partial u}{\partial z}\right)^2$$

Per unit of wall-area, the quantities can therefore be expressed by equation (3) with appropriate changes of symbols. The dissipation of energy per cycle per unit-length of channel is then

$$N = (\rho/2)\sqrt{\pi\nu T}\left[\int_0^b (\bar{u}_z - d)^2\, dy + 2\int_0^d (\bar{u}_z^2 + \bar{w}_z^2)\, dz\right] \qquad (13)$$

The average rate of dissipation is (N/T) and the total in a length of channel ℓ is

$$P_1 - P_2 = \int_0^\ell (N/T)\, dx \qquad (14)$$

Here P_1 is the power transported into the reach at x = 0 and P_2 is the power leaving at $x = \ell$.

From the equations stated one can predict h_2 and P_2 by a purely step-by-step analytical procedure but this method is tedious and less accurate for the purpose of comparing theory and experiment than the method used, namely, computation of the value of N at each station from the measured head, period, and depth and evaluating the right-hand side of equation (14) by graphical integration. Use of the measured wave-heights in computing the energy-loss eliminates the cumulative errors of the analytical step-by-step procedure in predicting wave-heights but in no way invalidates the comparison of theory and experiment.

Experimental verification

Waves were generated by means of a hinged flap at one end of a channel 12 inches wide, 60 feet long and 3 feet deep. Waves were absorbed both behind the flap and at the far end of the channel and reflections were imperceptible. Automatic control held the crank-speed during each revolution and gave the wave-flap a period of 1.15 seconds. The effective channel-width was altered by inserting braced panels of plywood which allowed the waves to pass on both sides. Heights, periods, and lengths of wave were measured by hook-gages and point-gages fitted with glow tubes. The temperature of water ranged between 68° and 70° F. The distance between gages No. 1 and No. 2 was 19.53 feet and between No. 1 and No. 3, 42.97 feet.

A summary of the experimental results appears in Table 1 together with the computed values of the power dissipated in bottom and sidewall friction. The measured power-losses ($P_1 - P_2$)

Table 1--Experimental and theoretical results

	One-inch channel				Three-inch channel		
L, ft	6.54	6.50	6.50	6.54	6.43	6.48	6.50
C, ft/sec	5.68	5.66	5.66	5.68	5.59	5.63	.....
d, ft	2.042	2.034	2.034	2.034	1.950	1.949	1.996
h_1, ft	0.399	0.310	0.236	0.067	0.129	0.093	0.229
h_2, ft	0.271	0.200	0.150	0.055	0.111	0.080	.....
h_3, ft	0.107	0.093	0.084	0.028	0.095	0.072	0.154
($P_1 - P_2$), ft-lb/sec							
Theory	0.193	0.129	0.075	0.0063	0.0253	0.0148	.....
Measured	0.180	0.118	0.0701	0.0051	0.0283	0.0146	.....
Error, per cent	+3.0	+8.6	+6.6	+23	-11	+1.4	.....
Theory	0.274	0.185	0.1081	0.0104	0.0455	0.0268	0.132
Measured	0.311	0.183	0.1031	0.0128	0.0497	0.0224	0.183
Error, per cent	-11.9	+1.1	+4.6	-1.9	-8.4	+19.8	-28

and ($P_1 - P_3$) are computed from the measured wave-characteristics and the differences are generally smaller than P_1, P_2, and P_3, resulting in occasional large percentage-errors. An apparently greater degree of precision would have been obtained had the computed and measured heads h_2 and h_3 been compared. Slow tank-surging, ripples, variations in channel-width and wave-generator speed, and the unavoidable errors in observation all contribute to the discrepancy between theory and measurement which has an average absolute value of 11 per cent. However, the measured losses are scattered about the theoretical values with the average of the predicted values less than one per cent greater than measured. A few measurements were made with the full 12-inch width of the channel but the energy-loss was too small in comparison with the transmitted energy for reliable comparison.

The transmitted wave-energy is distributed along the crest while the energy-loss by friction occurs at the walls and bottom and the effect diffuses inward. In a channel, very wide in compari-

son with the wave-length, appreciable difference in wave-height may occur between the center and the walls but, in these experiments, were not discernible. The effect of friction diffuses inwards but is counteracted by the outward flow of wave-energy from the center of the channel where the wave-height is a maximum and the result is that the waves are, within the accuracy of measurement, of uniform height.

The experiments show that the theory is sufficiently accurate for the purpose in mind, namely, to predict the width of channel necessary to obtain inappreciable energy-losses through wall-friction for a particular combination of depth, and period and length of wave. Since the power-loss is intended to be small, equation (14) may be rewritten for this purpose as

$$\Delta P/P_1 = (N_1/TP_1)\,\ell$$

Here $(\Delta P/P_1)$ is the fractional permissible power-loss and N_1 is the loss per cycle per unit-length of channel at the first station. By assuming different channel-widths and computing N_1, $(\Delta P/P_1)$ can be made to fit the desired condition.

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THE USE OF HYDRAULIC-LABORATORY METHODS IN GEOPHYSICAL PROBLEMS

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(Abstract)

This paper was an informal explanation of slides illustrative of geophysical problems attacked by laboratory methods. Illustrations were drawn from work at the Fluid Mechanics Laboratory of the University of California, Berkeley, and included periodic flow with free surface in porous media, wave-refraction around an island and over a submarine valley, waves moving over a sloping bottom, density-currents, electric analogy of flow to a slotted liner in petroleum-wells, tidal flow in a channel, models of ocean beaches and estuaries, transportation of bed-load and suspended material, seiches of finite amplitude, and friction in open channels.

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MODIFIED WHEATSTONE-BRIDGE ASSEMBLY FOR LABORATORY USE AND WATER-WELL EXPLORATION

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(Presented by J. F. Poland)

(Published with the approval of the Director, Geological Survey, United States Department of the Interior)

Introduction

Use of ground-water has tended to increase progressively in recent years and probably will continue to increase in the immediate future; thus, it is to be expected that ground-water supplies will become depleted or seriously overdrawn in some areas. With overdraft, the water-level or pressure-head of the fresh water falls so that salt water may be drawn into pervious beds along the ocean shore or near some other source of saline water. Bodies of ground-water have been so contaminated in some areas along the Atlantic, Gulf, and Pacific coasts of the United States and locally within the interior; some of these areas of salt-water contamination will tend to enlarge and others probably will develop. Problems encountered in the investigation of ground-water supplies so contaminated create a challenge to develop improved and more precise methods for quantitative evaluation of salt-water encroachment.

In connection with a cooperative investigation of ground-water conditions in the southern part of the Los Angeles coastal plain, the Ground Water Division of the Geological Survey, United States Department of the Interior, has designed and assembled a modified Wheatstone bridge particularly adapted to explore saline contamination of ground-water bodies by probing variations in the elec-

trical conductance of water in wells and in water-samples taken to the laboratory. This instrument, which is here described, affords a degree of precision much greater than has been possible heretofore with readily portable equipment, yet it can be manipulated very rapidly.

The Wheatstone-bridge circuit for measurement of electrical conductivity of water and soil solutions was pioneered by the United States Department of Agriculture and has been used by many investigators [see 1 of "References" at end of paper]. Improved methods and instruments gradually have brought precise control over laboratory measurements of conductivity. Also, field-measurements in water-wells by passing an electrical current across a water-gap, commonly suspended on a suitably energized two-conductor cable, have been carried on for a number of years [2], primarily to locate zones of contaminated water in wells. Recently, quantitative measurements of water-conductance in wells have been attempted [3] but the field-equipment available has not been precise, largely because it did not afford concomitant determinations of temperature and conductivity of water. Because the conductance of electrolytes varies about two per cent for each degree Centigrade through the natural range of temperature, this lack of concomitant values for conductivity and temperature restricted the procedure to relative evaluations of water-conductance. The instrument assembled by the Geological Survey affords the desired concomitant values, leads to evaluations of specific electrical conductance in a moderate degree of precision, and permits discrimination in the field of natural waters that differ only slightly in the character and amount of dissolved constituents.

Description of the modified Wheatstone bridge

General features--The instrument described here is adapted to three procedures, namely, (1) laboratory tests of water-samples using a standardized conductivity-cell, (2) field-tests of discharging wells, and (3) vertical traverses in wells with a suitable water-gap attached to an energized cable and coupled with a resistance-thermometer to measure water-temperatures. These procedures yield values of specific electrical conductance by using a conventional Wheatstone-bridge circuit to measure resistance across the calibrated water-gap.

In its general features the instrument embodies suggestions by G. A. LA ROCQUE, JR., as well as by the writers; the final design and assembly was by A. M. PIPER. Constructive criticism of the electrical circuits and some instrumental tests of the assembly were afforded by Messrs. BELLEVILLE and SCHOENFELD, technicians at the Radio Laboratory of the United States Forest Service, also by TEMPLE EHMSEN, radio technician of the municipal Police Department, all at Portland, Oregon. The assistance of these technicians is acknowledged with gratitude.

The Wheatstone bridge, which is the principal element of the instrument, is designed for operation with resistance-arms of about equal magnitude; also, for use with water-gaps or conductivity-cells of such proportions that their resistance is on the order of 500 to 1,000 ohms in waters essentially free from saline contamination. By changing the magnitude of the resistive components of the bridge-circuit the instrument could be adapted readily to water-gaps or cells of other proportions.

The resistive components of the bridge are sufficiently precise and the stray inductances and capacitances of the bridge-circuit are sufficiently compensated that unknown resistances can be measured to an accuracy of about 0.2 per cent or less in the range between 50 ohms and 1,000 ohms. The null-point indicator is an electron-ray tube or "magic eye", coupled across the bridge-arms and separately energized according to communications-technique. This type of indicator is highly sensitive and yet permits the bridge to be balanced rapidly. Further, it cannot be damaged by careless operation of the bridge; in this respect it is greatly superior to a galvanometer. Also, it can be read accurately in noisy or poorly illuminated surroundings, which are common at pumping wells; under such conditions it is superior to either earphones or galvanometer. As a whole, the null-indicator circuit is sensitive to an unbalanced potential equivalent to not more than 0.05 per cent of the unknown resistance.

The instrument is energized from either a 6-volt storage-battery or a 115-volt source of alternating current. Selection between these two sources of energy is accomplished by distinct power-supply cables; these attach to a common 12-pole socket in which the bridge and null-indicator circuits are so separated that none can be improperly energized.

Figure 1 shows the instrument assembled except for switch title-plates; Figures 2 and 3 are views of the chassis disassembled and arrayed for testing or adjustment. Figure 4 shows the circuit-diagram which is discussed in more detail later.

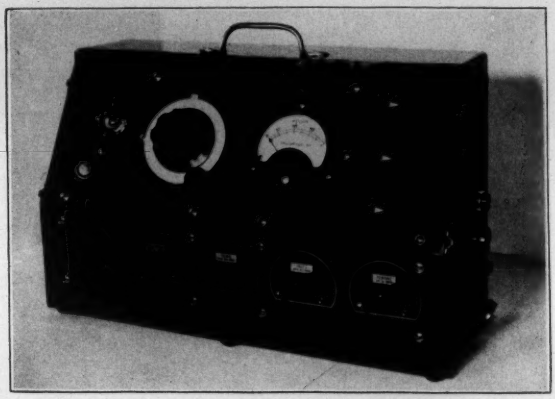
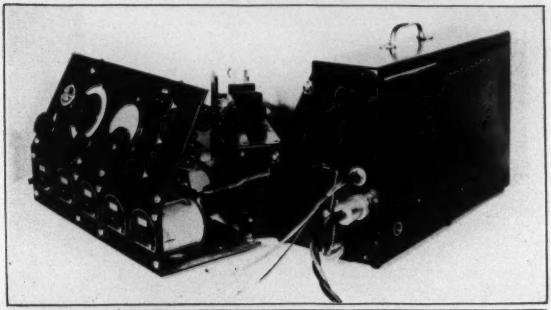
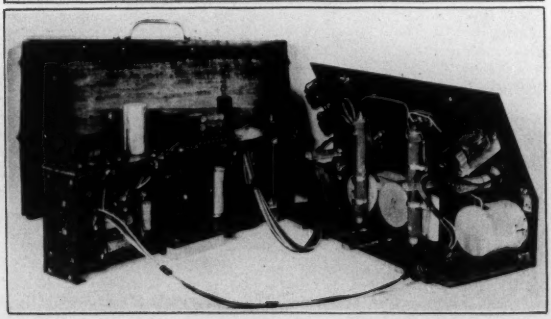


Fig. 1--Front view of Wheatstone bridge assembled except for switch-title plates





Figs. 2 and 3--Views of bridge-chassis disassembled and arrayed for testing or adjustment

The assembly is enclosed in a sturdy wooden case about 19 by 9 by 12 inches and weighs about 30 pounds. It can be disassembled rapidly by loosening two clamping screws recessed at mid-height in the rear panel of the case.

Power-supply--The bridge is energized with alternating current whose frequency is held low

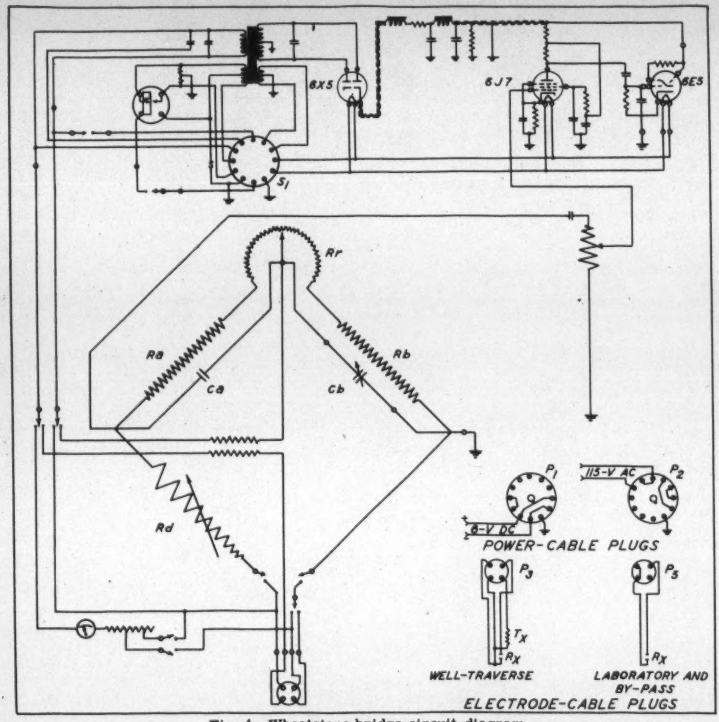


Fig. 4--Wheatstone bridge circuit-diagram

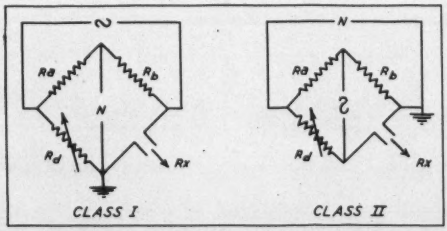


Fig. 5--Diagram showing bridge-circuits, Classes I and II

(50 to 120 cycles) to reduce capacitance-effects in the conductivity-cell or water-gap and in the long cable necessary for traversing deep water-wells. Direct current would have reduced these capacitance-effects to a relatively small value but would have led to polarization in the cell; thus, the use of direct current is not suited to accurate measurements of the conductivity of electrolytic solutions. Alternating current of medium frequency (about 1,000 cycles) is commonly employed in precision bridges of the hummer-type, but its use in this assembly would have no great advantage to compensate for an undesirable increase in capacitance-effects. The reader is referred to a paper by Hibbard and Chapman [4] for further discussion of frequency-selection versus capacitance-effects in the operation of a Wheatstone bridge.

In the laboratory, the bridge is ordinarily operated directly from a 115-volt lighting circuit; in the field, from a 6-volt storage-battery. The voltage transformations required for the bridge and null-indicator circuits are accomplished by an all-purpose transformer of the type commonly employed in portable radios adapted to operate from line-current or from a storage-battery. From this transformer one secondary coil supplies alternating current to a full-wave rectifier which in turn furnishes direct current at a potential sufficiently high to operate the plate-elements of the amplifying and indicating stages in the null circuit.

The circuit-diagram (Fig. 4) uses the conventional symbol for ground to indicate connections that are made within the instrument to reduce stray currents to the neutral potential or voltage reference-level. In laboratory operations it has not been found necessary to equalize this neutral potential with earth-potential by a connection to an external "ground". However, when the instrument is used in connection with vertical traverses in deep wells, appropriate connection of the equipment to an external "ground" may become critical. Some features of this problem will not be solved until the equipment has been used more widely.

Bridge-circuit--With respect to the application of electrical energy and to detection of balance, connections to the bridge-terminals might be in either of two ways, as shown diagrammatically in Figure 5.

As described and as shown on the circuit-diagram (Fig. 4), the bridge is assembled as in Class II of Figure 5. These two classes of assembly involve some fundamental differences in design of the circuit by which energy is applied to the bridge-terminals; also considerable differences in performance characteristics of the bridge- and null-circuits.

With a 115-volt source, a Class-I circuit, and a voltage-divider of suitable proportions between source and bridge-terminals, the voltage across the terminals can be held reasonably close to the maximum tolerance of the bridge-elements throughout the range of unknown resistances. Table 1 shows the range in bridge-voltage, current-drain, and signal-strength to the null-indicator circuit if a 2,500-ohm voltage-divider is placed across the 115-volt source with 1,500 ohms between the taps to bridge-terminals.

Table 1--Performance of 2,500-ohm voltage-divider across 115-volt source with 1,500 ohms between taps to bridge-terminals

(Class I circuit; bridge balanced for unknown resistances from 1,000 ohms to 1 ohm)

R_x (ohms)	Electromotive force across bridge-terminals (volts)	Current-drain from bridge-terminals (milliamperes)	Current-drain from source (milliamperes)	Signal-strength for deviation from balance of 0.1 per cent (millivolts)
1,000	43.5	42	71	11
500	36.6	54	78	9
100	16.1	88	99	4
50	9.5	98	105	2.4
10	2.2	111	113	0.6
1	0.23	115	115	0.06

With a Class-II circuit and a 115-volt source, and a fixed resistance of 2,000 ohms introduced in series with the bridge, fair voltage-regulation is accomplished. Table 2 shows the degree of voltage-regulation so obtainable, current-flow, and signal-strength.

Table 2--Performance of 2,000-ohm resistance in series with bridge across 115-volt source

(Class-II circuit; bridge balanced for unknown resistances from 1,000 ohms to 1 ohm)

R_x (ohms)	Electromotive force across bridge-terminals (volts)	Current-flow (milliamperes)	Signal-strength for deviation from balance of 0.1 per cent (millivolts)
1,000	39.0	38	10
500	32.1	41	7
100	25.7	45	2.1
50	24.8	45	1.0
10	24.1	45	0.23
1	23.9	45	0.024

A Class-II circuit was adopted in preference to a Class-I circuit because (1) the resistance of the cable used in deep wells can be made self-compensating with one less conductor in the cable, (2) the Class-II circuit maintains equal resistance in the two arms across which the power is applied so that the current passing through the water-gap can be held essentially constant throughout the range of field-resistances, in sharp contrast to high current-transmission through the cell when low resistances are measured with the Class-I circuit, and (3) throughout the range of unknown resistances the bridge is protected against overload by inadvertent error in operation.

The series resistors introduced between the power-source and the bridge-terminals control the potential across the bridge between about 25 and 40 volts throughout the range of water-gap or temperature-coil resistances (see Table 2). As can be seen from the wiring diagram (Fig. 4), the bridge is equivalent to two resistances in parallel across the power-source; one includes R_a, R_d, and part of R_r, the other includes R_b, R_x, and the remainder of R_r. This circuit is most advantageous when the conductors to the unknown resistance are long, as in deep-well traverses, because resistance, inductance, and capacitance in the cable can be compensated between opposite arms of the bridge without introducing appreciable resistance in the null-indicator circuit and with the fewest possible conductors. R_a and R_b are nonvariable resistors of 1,000 ohms. R_r is a ratio resistor of 100 ohms for fine adjustment. The bridge can be balanced by varying R_d, a variable resistor composed of five "decade" units in steps from 0.1 ohm to 1,000 ohms. When successive readings are taken on unknown resistances of approximately the same magnitude, the bridge can be balanced quickly by operating only the ratio-resistor.

The conductivity-cell and the long cable employed in well-traversing introduce appreciable capacitance into the bridge-network, which would obscure the null-point indication unless compensated. The necessary compensation is accomplished by a nonvariable condenser, C_a, in parallel with arm R_a and a variable condenser, C_b, in parallel with arm R_b. The capacitance of the nonvariable condenser is about equal to the maximum capacitance of cell and cable; the variable condenser has a maximum capacitance at least twice that of the nonvariable condenser. Thus, capacitance-effects in cell and cable can be fully compensated whether they are additive or subtractive with respect to the fixed capacitance. If additive, the variable condenser compensates the sum and, if subtractive, the difference.

The accuracy with which any bridge-network can be balanced depends primarily upon the magnitude of the applied voltage and the sensitivity of the detector. The flow of current is controlled by the voltage applied and by the net resistance of the network. In the uses to which the instrument here described is put, the greatest flow of current that can be allowed--and hence, the maximum voltage applied to the bridge--is fixed by the current-tolerance of the bridge-components and by the maximum amount of electrical energy that can be dissipated as heat in the water-gap or in the resistance-thermometer without causing the null-indicator to "crawl". The voltage applied to this instrument advisedly has been regulated close to the maximum that can be tolerated, in order to gain in precision. Also, the voltage is so regulated in order that failure of the null-indicator to "crawl" as the water-gap is lowered into a deep well can be taken to indicate that the cable is free its full length; if the cable were lodged there would be no circulation of water through the gap, the resistance of the gap would diminish as heat was dissipated there, and the null-indicator would "crawl".

The strength of signal imposed on the null-circuit is a function of applied voltage, bridge-unbalance, and cell-resistance. Table 2 shows that a weak signal is generated when the water-gap is immersed in salty water of high conductivity and when the unbalanced resistance in the bridge-network is reduced to within 0.1 per cent of the resistance of the gap. Nevertheless, the one stage of audio-frequency amplification in the null-indicator circuit is sufficiently effective that water-gap resistances on the order of 50 ohms can still be measured to a precision of 0.2 per cent in the laboratory cell and to approximately that precision when deeply immersed in wells. When the water-gap is immersed in fresh water of low conductivity a strong signal is generated; until the bridge-network has been brought nearly to balance, a variable portion of this signal voltage is by-passed to "ground" in order that the output voltage from the amplifier will not exceed the range to which the electron-ray tube will respond.

By-pass circuit--Approximate values of water-conductance can be obtained by measuring the flow of electrical current across a suitable water-gap in the by-pass circuit. This procedure has been used commonly in tests for saline contamination of ground-water by the pumping method [5].

This by-pass circuit is energized by alternating current at 115 volts; it can accommodate currents as large as 100 milliamperes. It comprises a milliammeter, a controlling resistor, and a water-gap suited for insertion in the discharge line of a pumped well. Appropriate switches provide for passing the current through the water-gap or for shunting the current ahead of the gap to determine voltage on the circuit. Both water-gap and shunt cannot be in circuit simultaneously; a single switch selects between the two circuits and affords readings of line-voltage and current-flow across the water-gap almost simultaneously. These two variables being known, the total series impedance of milliammeter, controlling resistor, and water-gap is readily computed from Ohm's law. The impedance of meter and resistor is essentially nonvariable and has been determined as a constant of the instrument; the residual impedance is that of the water-gap.

By an appropriate switch, the water-gap that is inserted in the discharge line of a pumped well can be connected at will to either the by-pass circuit or the bridge-network; thus, water-gap resistance can be read precisely with the bridge. In field-practice it has been found entirely feasible to measure the resistance of the by-pass water-gap in the bridge-network and to use the milliammeter largely to indicate abrupt changes in conductance of the water.

Application to field-problems

In connection with investigations of salt-water encroachment, the chemical character of ground-waters usually is studied by one or more of three general methods: (1) Collection and analysis of individual samples of water from all available wells during as short an interval of time as is feasible, to delimit the areal extent and degree of the encroachment; (2) analysis of samples taken successively in time from a pumped well, to ascertain the degree of salt-water contamination in that well and possibly to delimit the depth at which the salt water enters; and (3) analysis of samples taken successively in depth within a well, particularly if the well is pumped and tests are continued for a considerable period of time, to determine the depth of contaminated zones and the degree of contamination.

In the water-samples one or more critical constituents can be determined in the laboratory by chemical means. Measurements of electrical conductivity can also be made to supplement the chemical analyses; for a particular area in which the ground-waters are much alike chemically, these measurements will afford an approximation of the total electrolytic content, and hence, of total dissolved solids. Data from such tests can be plotted on a map to outline areas of contamination that warrant more intensive study.

So far as is known to the writer, Mendenhall [6] was the first to measure the electrical resistance as an index to the relative chemical quality of the ground-waters in an extensive area. For such a procedure the instrument described in this report will afford values of conductivity to a degree of precision not heretofore possible in the field with readily portable equipment; if water-temperatures are determined within a small range, say 1°F, approximate values of specific electrical conductance result.

If pumped or flowing wells are sampled successively in time, subsequent chemical analyses or measurements of conductance will indicate progressive changes in water-quality. This method gives definite information concerning the amount of contamination; it may indicate the manner of salt-water entry [7] and, under certain conditions, the approximate location of leaks [8]. With the apparatus described here and a conductivity-cell inserted in the pump-discharge or in a water by-pass, measurements of electrical conductivity can be taken at very close time-intervals; samples

can be collected simultaneously for substantiative chemical analyses. If qualitative determinations are adequate, the fluctuations of current-flow with time can be read from the milliammeter and plotted for study.

Vertical traverses in wells can be made with mechanical samplers to collect samples at selected depths, with a conductivity-cell suspended on an energized cable to obtain measurements of conductivity at desired intervals, or by a combination of these two methods. The current-meter method can also be used to locate salt-water leaks in water-wells [9].

With the apparatus here described it is proposed to make simultaneous traverses of wells with a conductivity-cell and a resistance-thermometer, both energized through a multiple-conductor suspension-cable. The thermometer-assembly comprises a coil of metallic wire with a high thermal coefficient of resistivity, such as nickel, electrically separated from but thermally coupled to a metallic sheath by a dielectrical fluid. Thus, if the temperature of the water surrounding the conductivity-cell is determined from the resistance-value of the calibrated coil, the water-conductance can be expressed as specific conductance at standard temperature.

Adequate determination of water-temperature is critical in the interpretation and comparison of data from vertical traverses in deep wells. Thus, in the Los Angeles coastal plain the temperature of waters pumped from wells ranges from about 66° to 96°F. This range might be encountered in a single well that tapped successive aquifers to a depth of about 1,600 feet below the land surface. Under such conditions, if all aquifers contained water of identical chemical character, the actual electrical conductivity of the waters would range about 33 per cent, although their specific conductance at standard temperature would be the same.

In wells that are contaminated by salt water this dual traverse, combined when necessary with a test by the pumping method, should indicate the depth of the contaminated zone and give approximate quantitative values for the degree of contamination. It is hoped that corresponding data from uncontaminated wells will prove sufficiently accurate to aid in geologic and hydrologic correlations within a particular ground-water area and to afford useful comparisons between separated areas.

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THE COLORADO RIVER AQUEDUCT AS A SUPPLEMENT TO LOCAL WATER-SOURCES

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Deliveries of Colorado River water to member cities of The Metropolitan Water District of Southern California began here at Pasadena on June 17, 1941, after an eight-year aqueduct-construction period that had been preceded by an equally long program of surveys, investigations, and planning. To many of us who have worked on the project, this date naturally seemed an end and a climax, rather than the real beginning of an even more important, if less exciting, period of operations, for which all earlier work had merely been a preparation. So before passing to present problems of technical interest, as indicated by the assigned title, the aqueduct had best be located and its construction completed for you briefly. It has been so often and thoroughly described in detail in many technical journals, however, that little repetition of general data is now justified.

Aqueduct description and cost--Colorado River flood-waters, desilted and stored in Lake Mead above Boulder Dam, are pumped by means of Boulder Dam power through a vertical lift of 1,600 feet at five pumping plants. The Intake Pumping-Plant is 150 miles south of Boulder Dam, two miles above Parker Dam on the shore of Lake Havasu, which completes the desilting of the water while reducing the necessary pump-lift by 72 feet. The last pumps are west of Desert Center (so realistically and literally named, a spot of fond, midsummer memories) at the barren Hayfields, 130 miles from the Colorado River. The main aqueduct is built for the full future capacity of 1,500 second-feet (except for deferred pump-units and the second barrel of siphons), and includes tunnel, canal, conduit, and siphon-sections as required by topography, cross-drainage, and considerations of ultimate economy. It extends 242 miles to Lake Mathews, the terminal reservoir of 107,000 acre-feet capacity formed by Cajalco Dam and Dike. A distribution-system, with tunnels and pipe-lines of half capacity (750 s-f) then continues to the softening and filtration plant at La Verne, on past the Morris Reservoir in San Gabriel Canyon (for emergency and regulating storage), and through pipes of diminishing capacity to all District cities, with present terminals at Santa Monica, Santa Ana in Orange County, and Palos Verdes Reservoir near Long Beach and Torrance.

The aqueduct-project was financed by a bond-issue of $220,000,000, of which $180,600,000 was issued and is outstanding, at an average interest rate of slightly less than four per cent. Preliminary work was completed in 1930, simultaneously with the collapse of the normal bond-market, so that it was necessary to dispose of the bonds to the Reconstruction Finance Corporation (Self-Liquidating Division). The bonds have long since been resold to the general public, however, and incidentally at a premium and net profit to the Federal treasury of $13,500,000. A summary of costs of principal features is given in Table 1.

Table 1--Colorado River Aqueduct construction-costs

Surveys and investigations	$ 4,600,000
Right of way and lands	4,100,000
Construction utilities, roads, telephone-lines, etc.	2,900,000
Parker Dam	7,200,000
Power transmission-lines	2,700,000
Pumping-plants (5), including three pumps at each	15,950,000
Main aqueduct, 242 miles (tunnels, canals, conduits, and siphons)	103,400,000
Distribution-system (tunnels and pipe-lines)	33,000,000
Terminal storage-reservoirs	13,400,000
Subtotal	$187,250,000
Deferred items (one-half-capacity project two additional pumps for each plant)	3,750,000
Additional distribution-lines	7,000,000
Indicated cost of planned one-half-capacity project	$198,000,000
Compared with 1931-project bond issue of	$220,000,000
Saving for same project-capacity and features of	10 o/o
Present softening-and-filtration plant (not included in initial plans or bond-issue)	$ 3,700,000
Additional softening unit for 600 s-f total	5,300,000
Estimated cost of one-half-capacity project	$207,000,000
Total ultimate construction-cost, excluding water-treatment	$257,500,000
Compares with 1931 bond-issue estimate of	$283,536,000
Total ultimate construction-cost, including water-treatment	$274,000,000

Of chief significance in such a summary of cost is the fact that the project has been built for ten per cent less than the authorized bond-issue. This result was not achieved easily or accidentally, but only by a well-coordinated combination of factors which properly must share the credit, including: (1) An exceptional Board of Directors, absolutely non-political, composed of outstanding men of varied professional and business activities; (2) able, energetic, and honest management, as personified by the late Frank E. Weymouth, in general charge from 1929 to 1941; (3) experienced, skillful contractors and engineers, as made available by depression conditions when work was started; and (4) employees of all classes--over 35,000 in number--far above the average or present standards in experience and skill, loyalty, and morale, with practically no labor disputes until near the end; this also largely a result of then-prevailing conditions of unemployment.

Considering both costs of labor and material, it has been estimated that the present project would have cost at least $100,000,000 additional if started two or three instead of nine years ago. An example is the construction power-line, which in place prior to wrecking and salvaging sold for more than its original cost. With present emergency conditions, aqueduct-construction would have been indefinitely delayed and vastly more costly, so that by its time-schedule, the economics of using Colorado River water to supplement local sources have been greatly benefited.

Annual costs and water-rates--But like any stand-by or supplemental feature, such as a spare pump or extra well for a small-scale example, the aqueduct's annual costs are practically fixed in amount, whether 50 s-f or 500 s-f are diverted and utilized. Therefore, in order to encourage and permit the use of Colorado River water where this might be desirable for engineering and other reasons, the District Board of Directors had adopted water-rates which in its judgment will result in a minimum District tax-rate. These are $8.00 per acre-foot for untreated water and $15.00 per acre-foot for softened, filtered water, with a present tax-rate of 48 cents per $100 of assessed valuation. As water-use increases and both annexations and growth produce a larger assessed valuation, this tax-rate will gradually be reduced. Several member cities have consistently reduced or even eliminated this District tax by advance payment of same from retail water-revenues. The division of the aqueduct water-costs for stand-by and supplemental purposes, between the water-consumer and the taxpayer within each community, is therefore not arbitrary or fixed but remains within the control of the officials of each member city, to be varied as may best suit local conditions. For irrigation-use, the aqueduct tax is equivalent to an addition of generally not over $1.00 per acre-foot to the water-rate, depending on the assessed valuation of the land and the amount of water used.

A major factor in reducing the annual cost of Colorado River water and thereby enabling it to be used here more promptly and generally, is the recent Boulder Canyon Project Adjustment Act and revised power-contracts, with the Boulder Dam rate of interest changed from four per cent to three per cent, and repayment of the project's flood-control allocation deferred for 50 years. The annual saving in aqueduct-power (falling water) cost will average $700,000 for the next 45 years, and including credits for recent excess payments and similar savings in generator-costs, will approximate $1,000,000 per year for the next several years as compared with costs under the original power-contracts. Present emergency-power demands also indicate that a large block of power, contracted for but not as yet needed for aqueduct pumping, will be put to use without further cost to the Metropolitan Water District.

Present status of aqueduct-project--As yet the aqueduct has become the sole or main source of water-supply for only one city, Santa Monica, but it has been used as a supplemental source by ten of the Southern California cities, including a small consumption by Los Angeles. Physical connections have been constructed, however, so that Colorado River water is now available on short notice for the emergency or supplemental water-requirements of any of the 13 District cities, including Pasadena, Long Beach, Glendale, Burbank, Beverly Hills, etc. The 13 present members compose over 70 per cent of the population and about three-fourths of the water-consumption of the Los Angeles metropolitan area, as this is defined for census purposes, with its total now in excess of 3,000,000 inhabitants. Aqueduct-water service is strictly limited to the areas of these member cities, and of districts which may annex and may include unincorporated irrigated tracts, but at present the aqueduct is supplying only domestic, industrial, and general municipal water-uses.

The Metropolitan Water District boundaries are just being extended, for the first time since the aqueduct-bond election of 1931, by the annexation of the Laguna Beach Municipal Water District, including the city of Laguna Beach and contiguous lands to the north and south of that city along the Orange County coast-line. The immediate cause of this annexation is the same as has led to the full initial use of Colorado River water at Santa Monica--the rapid and serious increase

in chloride content of ground-water supplies in several localities near the coast-line. Thus the chief present demand for Colorado River water is a result of its superior quality, after softening and filtration, compared with many of the local ground-water sources, rather than any immediate and acute shortage of water.

This conclusion is certainly contrary to the expectations of both the advocates and opponents of the project when it was authorized ten years ago by a five-to-one majority of the voters. Then its chief support was due to the long and severe regional drought, which indeed continued almost unbroken until 1937, and opposition centered largely on quality questions--salinity, silt, chlorides from the Virgin Valley, fluorine, boron, etc. These worries all have vanished as will be explained, but with them also has gone the drought for the time being. Five successive seasons that have averaged about 50 per cent above normal precipitation, and the current one still about normal in the Los Angeles Area and far in excess of the average in some localities such as San Diego, have helped greatly in relieving the previous serious ground-water-supply situation. Without anticipating the data and conclusions of later papers, it is general knowledge that ground-water storage in the smaller basins near the mountains has been fully replenished, giving a two or three-year margin of safety against shortages. Water-levels also have risen rapidly in some of the larger basins that have continued without a pumping overdraft, such as the Upper San Gabriel and the San Fernando valleys. Even in the coastal sub-basins, long burdened with relatively large overdrafts and cut off from the direct replenishment of mountain streams, with percolation further reduced by the rapid extension of roofed buildings, paved streets, and flood-control channels, the wet years have served at least to check the downward trend of water-levels and have relieved the worst immediate problems. Depleted basins have been further aided by reduced pumping for industrial and domestic purposes during the depression years, and more recently, by decreased irrigation-pumpage in the seasons of heavy rainfall. Some wells were abandoned or pumping at least suspended, thus aiding other nearby pumpers, particularly in the Harbor District and other southern sections of Los Angeles, when extensions of Owens Aqueduct piped supplies made a better quality of water available.

The general result of all these factors is that for the next year or two at least, the chief function and value of the aqueduct is evidently as insurance against future drought- and water-shortages, for no one familiar with conditions here can doubt that severe droughts will again occur at frequent intervals in the future, as in the past. In some cases where softness, filtration, and other quality-standards outweigh strict considerations of economy, increasing quantities of Colorado River water will be consumed long before this is forced by actual shortages. But the project is planned and designed primarily to supplement local sources rather than to replace them, and demands on it will therefore vary greatly as between wet and dry periods. Looking further to the future, the capacity and water-rights of the aqueduct enable the supply for the Southern California Coastal Plain to be doubled from a present average of 0.7 foot to an assured total of 1.4 acre-feet per acre of habitable area. This provision for future growth of population and industry, in the light of present trends of development here, once more looks fairly conservative as compared with natural doubts, often expressed during recent years of sharply reduced rates of growth in Southern California.

Quality of Colorado River water--Second only in importance to such economic factors as the cost of the aqueduct-project and the adoption of water- and tax-rates, are the varied problems of water-quality, when considering the use of Colorado River water for supplementing local sources. Much opposition to the project naturally centered on the obvious facts of pre-B.C. (Boulder Canyon) high silt-content, and of excessive salinity during seasons of low flow. The Virgin Valley salt-beds were once even more notorious but with the filling of Lake Mead, these bogies seem finally submerged and forgotten. The surprise and chagrin of one persistent and influential critic is recalled when he took his first boat ride on the reservoir; admired the clear, blue water, and found it refreshingly palatable to drink; then caught his first bass. When congratulated on hooking such a fine salt-mackerel, he admitted to being at last convinced he had been merely a sucker for propaganda, after all. For though large, as salt outcrops go, these were negligible in comparison with the immense storage of Lake Mead and as predicted, were quickly sluffed over with silt. No material increase in chlorides was apparent even in samples taken but a short distance from the shore-line of the salt beds. Likewise, silt is disposed of for two or three hundred years at least, but long before then the construction of Bridge, Glen, and other upstream reservoirs will have indefinitely prolonged the life of the Boulder Canyon Reservoir. And excess salinity, formerly varying from 1,000 parts per million to as high as 2,000 parts per million in some winter months, is now prevented by mixture in Lake Mead with the pure flood-flows of the early summer.

Before reference to more serious and genuine problems, the fluorine hoax might also be disposed of once more. The only available drinking water for a few persons along Muddy Creek, a

tributary of the Virgin River but which now flows directly into Lake Mead, is highly mineralized ground-water with a large fluorine content. The flow of Muddy Creek is chiefly consumed for irrigation and in any case, is inappreciable after mixture with the flow of the Colorado River. But a large group of very sincere clubwomen were naturally alarmed and horrified when, after inspecting the badly mottled teeth of the Overton village school children, while ice cream was consumed to induce the shy ones to open their mouths, the ladies were informed that such bad teeth were to be the future fate of all the children of Los Angeles and vicinity. So fluorine became a carefully nursed political issue for a mayor that was soon to be beaten at the polls, and the fight was on to stop all aqueduct-construction work. Surprisingly enough, chemists could not agree at once on how to determine accurately such slight amounts of fluorine in solution, though they have since found that Colorado River water contains only about 20 per cent of the fluorine threshold-of-danger content. So a clinical survey among all Imperial Valley dentists was made by U.S.C. Dental College, revealing that no person born and raised in Imperial Valley, with only Colorado River water available, had ever been affected by mottled tooth enamel. But in the meantime, lynching was the very best fate that aqueduct-engineers could reasonably expect.

The question of boron was also very serious, particularly to citrus growers considering the use of Colorado River water for the supplemental irrigation of groves. Fortunately, however, much progress had been made on boron research before aqueduct-construction was begun, so that ample official analyses were soon made available to prove the safety of Colorado River water in this respect. Of recent years the Quality of Water Division of the United States Geological Survey had added both boron and fluorine to its routine analyses of daily samples of Colorado River water. The boron average, weighted in proportion to the river-discharge, is about 15 parts per 100 million, or less than one-third the minimum suspected of causing damage.

Aqueduct treatment-plant--As the aqueduct is primarily for domestic and industrial use, the excessive hardness of raw Colorado River water was evidently its most serious disadvantage. It was originally planned to postpone softening the water until after a considerable consumption of aqueduct-water had occurred, possibly on the assumption that during an acute drought, water-users cannot be too particular about the softness of supplemental sources. Also, probably many relied on mixing Colorado River water with some of the depleted local sources. But as actual operation received more detailed study toward the end of the main period of construction, and the wet years after 1937 afforded more time in which to complete the project, the decision was reached to soften the water for immediate, initial deliveries.

A detailed description of the treatment-plant can be better given later, during our inspection of the process while in operation, but it is designed for the lime-zeolite method. This was selected chiefly for economy, as salt here is relatively cheaper than soda ash, but it has other advantages of close control of the effluent quality, easier sludge-disposal, etc. Lime is first added to the raw water to reduce the carbonate hardness, before passing a computed portion of the flow through the zeolite-beds which produce zero hardness. This completely softened split-portion is then remixed with the by-passed part of the flow to give a discharge of any desired degree of hardness. Of recent months, however, it has become preferable to omit entirely the lime-treatment because long storage of the water in the successive reservoirs from Lake Mead to Lake Mathews so greatly reduced the bicarbonate content, at times almost to the vanishing point. This effect varies seasonally, however, with the increased evaporation and more rapid growth of algae in summer, so that the split treatment may again be put in use shortly at the aqueduct-plant. Table 2 therefore shows analyses of raw and softened Colorado River water, as the latter was produced first by the combination lime-zeolite treatment and more recently by zeolite only. The lime-treatment prevents a material increase in total dissolved solids, in fact effects a reduction of the concentration-value in milligram equivalents, and for this reason its use is desirable.

Practical details of plant-operation can be made clearer this afternoon, but as was anticipated, initial operating difficulties were encountered in some of the city distribution-systems, with red water and turbidity. These local troubles were generally due to the new, softer water causing a sloughing off and cleaning of slime-deposits in the long-used pipes, and required considerable flushing of distribution-systems. In other cases, variation of the pH and carbonate content, etc., of the plant-effluent soon cured the trouble. Chiefly to be noted in Table 2 are the relatively high values of total dissolved solids and the percentage of sodium. The first is considered a temporary condition, as will be explained in connection with Lake Mead investigations. The high percentage of sodium seems unavoidable, however, if the water is to be softened to a satisfactory degree, and this continues to be a matter of considerable concern to soil experts. It does not affect most of the proposed irrigation-uses, which will be with raw Colorado River water east of the treatment-plant, and this raw water is safely below the safety-limit of 50 per cent which has been suggested. It does call for further study as regards use in city parks and gardens, however, and

Table 2--Colorado River water analyses, typical raw and softened (finished) samples at Metropolitan Water District Treatment-Plant, La Verne, California

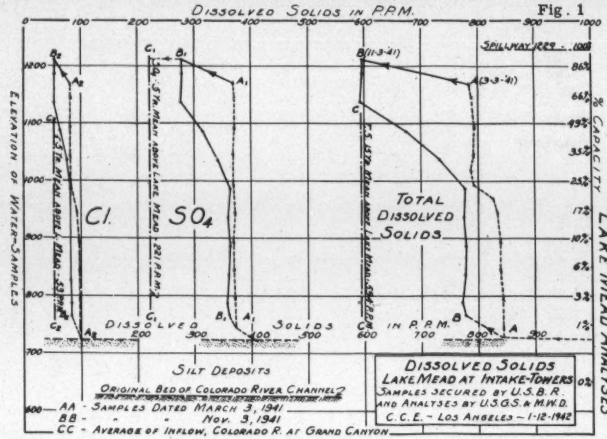
Constituent	August 22, 1941				January 10, 1942		January 4, 1942	
	Raw water		Lime-zeolite softened		Raw water		Zeolite softened	
	ppm	Mg.eq.	ppm	Mg.eq.	ppm	Mg.eq.	ppm	Mg.eq.
MWD Lab. No.	(117)		(120)		(383)		(362)	
Calcium, Ca	90	4.49	24	1.20	95	4.74	25	1.25
Magnesium, Mg	30	2.47	7	0.58	33	2.71	11	0.90
Sodium (and Potassium), Na	121	5.26	229	9.96	132	5.74	267	11.61
Iron, Fe	0.1	----	0.0	----	0.1	----	0.0	----
Bicarbonate, HCO_3	109	1.79	12	0.20	139	2.28	143	2.35
Carbonate, CO_3	----	----	17	0.57	0	----	13	0.43
Sulphate, SO_4	370	7.70	374	7.78	384	7.99	386	8.03
Chloride, Cl	97	2.74	114	3.21	104	2.93	105	2.96
Nitrate, NO_3	----	----	----	----	0.6	0.01	0.6	0.01
Silica, SiO_2	2	----	8	----	3	----	7	----
Alumina, Al_2O_3	----	----	----	----	0.3	----	0.2	----
Boron (av.), B	(0.15)	----	----	----	(0.15)	----	----	----
Fluorine (av.), F	(0.3)	----	----	----	(0.3)	----	----	----
Dissolved solids	765	----	779	----	821	----	886	----
Concentration-value	----	24.45	----	23.50	----	26.40	----	27.54
Hardness as $CaCO_3$								
Total	348	----	89	----	373	----	108	----
Carbonate	89	----	38	----	114	----	108	----
Non-carbonate	259	----	51	----	259	----	0	----
Phenol alkalinity	0	----	14	----	0	----	11	----
M. O. alkalinity	89	----	38	----	114	----	139	----
Turbidity	0.4	----	0.2	----	0.5	----	0.2	----
Carbon dioxide, CO_2	1	----	0	----	4	----	1	----
Hydrogen ion, pH	8.1	----	9.6	----	7.7	----	8.5	----
Per cent sodium	43	----	85	----	43	----	84	----
Temp. when sampled, °F	72	----	72	----	57	----	57	----

makes adequate drainage of even greater importance. Bad soil-effects that have been predicted can probably be prevented by applications of lime or possibly very economically by use of the treatment-plant sludge. Immediate or even future consequences are somewhat discounted by the long use, since 1929 in fact, of softened water on parks and gardens in Beverly Hills, with a similarly high percentage of sodium but without decreasing the evident beauty of that city. But the percentage of sodium remains a problem of great local importance.

Lake Mead investigations--Except for softening effects and purification by filtration and chlorination, the standard of the aqueduct-water is of course directly dependent on the quality of the discharges at Boulder Dam. As Lake Mead began to fill in 1935, it became apparent that density-currents and stratification-effects were to be of great importance there. On several occasions, in 1935 and 1936, with the lake clear and blue as far upstream as could be seen (70 to 90 miles of clear water at the time, in fact), the same old silty Colorado River water filled the channel below the dam, an uncanny sight quite unforgettable and unexpected. The problem was of sufficient general interest to lead to the formation, in March 1937, of a Density Currents Committee of the National Research Council under the chairmanship of Herbert N. Eaton of the National Hydraulic Laboratory, to undertake its study at other lakes and reservoirs as well as in laboratories. The Committee has a large national membership, including representatives of numerous Federal bureaus involved in such research and of other interested organizations, and a capable subcommittee has devoted special attention to Lake Mead. Local members of the Committee include Robert T. Knapp of the California Institute of Technology, Raymond A. Hill, and the writer. A voluminous report is shortly to be issued that will throw much light on practical as well as theoretical aspects of reservoir-problems at Lake Mead, Elephant Butte, and elsewhere.

Meanwhile, for present purposes, a few preliminary drawings are included to show recent conditions at Lake Mead. Temperature-distribution with depth and stratification-effects are illustrated in Figures 3 and 4. Of even greater interest for aqueduct-purposes are Figures 1 and 2, showing distribution of salinity and hardness-factors with depth, as of November, compared with

March, 1941. The great improvement within this short period is due to the above-normal runoff, the largest since 1929, of 17,000,000 acre-feet or about 14 per cent above normal, which practically filled the reservoir and has caused a large spill as well. This inflow compares with an average of only 74 per cent of normal during the prior storage-years 1935 to 1940, with the outflow then limited to irrigation- and power-requirements. A summary of such discharges, with average dissolved solids and hardness above and below Lake Mead since 1925, are listed in Table 3 from published and unpublished records of the United States Geological Survey. The plotted records for 1941 are based on samples secured by the United States Bureau of Reclamation at monthly intervals since 1937, at 25-foot-depth spacing, midway between the Boulder Dam intake-towers. Half of these samples have regularly been analyzed by the Geological Survey at its Washington, D. C., laboratory, and half by the Metropolitan Water District. These samples now total


DISSOLVED SOLIDS IN P.P.M.
Fig. 1
ELEVATION OF WATER-SAMPLES
% CAPACITY
LAKE MEAD ANALYSES
Cl.
SO4
TOTAL DISSOLVED SOLIDS
SILT DEPOSITS
ORIGINAL BED OF COLORADO RIVER CHANNEL
DISSOLVED SOLIDS LAKE MEAD AT INTAKE-TOWERS
SAMPLES SECURED BY U.S.B.R. AND ANALYSES BY U.S.G.S. & M.W.D. C.C.E. - LOS ANGELES - 1-12-1942
AA - SAMPLES DATED MARCH 3, 1941
BB - " NOV. 3, 1941
CC - AVERAGE OF INFLOW, COLORADO R. AT GRAND CANYON
HARDNESS AS CaCO3, IN P.P.M.
Fig. 2
CARBONATE HARDNESS
NON-CARB. HARDNESS
TOTAL HARDNESS
HARDNESS AS CaCO3 IN P.P.M.
HARDNESS OF WATER LAKE MEAD AT INTAKE-TOWERS
SAMPLES SECURED BY U.S.B.R. AND ANALYSES BY U.S.G.S. & M.W.D. C.C.E. LOS ANGELES - 1-12-1942

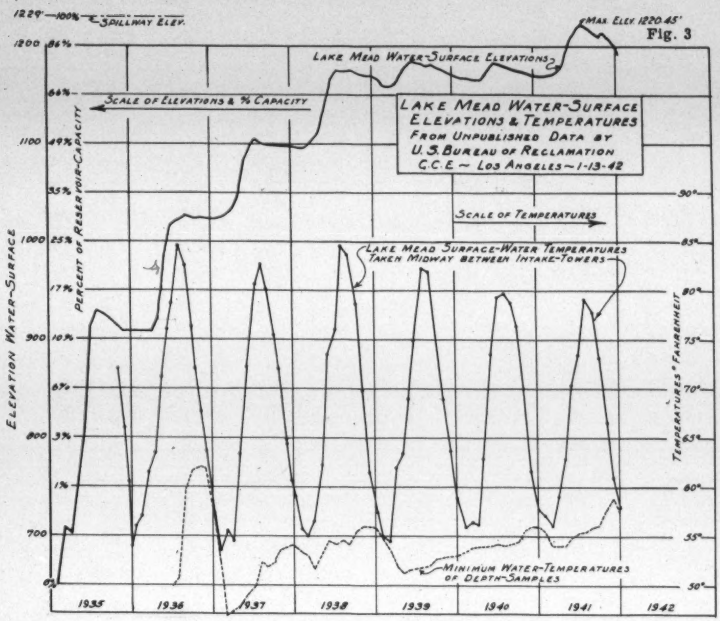


Fig. 3
Spillway Elev.
Max. Elev. 1220.45'
Lake Mead Water-Surface Elevations
Scale of Elevations & % Capacity
Lake Mead Water-Surface Elevations & Temperatures
From Unpublished Data by U.S. Bureau of Reclamation C.C.E. – Los Angeles – 1-13-42
Scale of Temperatures
Lake Mead Surface-Water Temperatures Taken Midway between Intake-Towers
Minimum Water-Temperatures of Depth-Samples
Elevation Water-Surface
Percent of Reservoir-Capacity
Temperatures "Fahrenheit
1935
1936
1937
1938
1939
1940
1941
1942

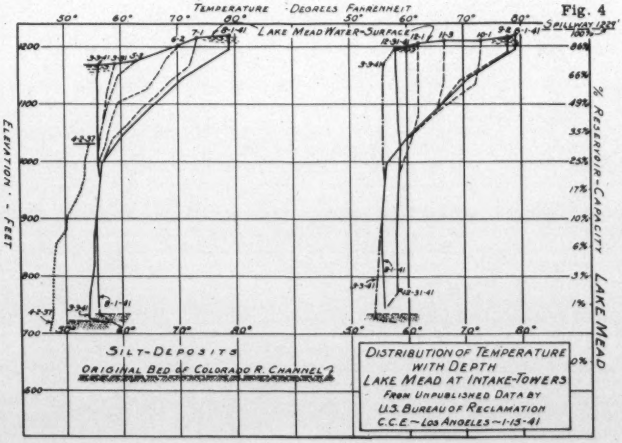


Fig. 4
Temperature - Degrees Fahrenheit
Lake Mead Water-Surface
Spillway 1221'
Elevation - Feet
% Reservoir-Capacity
Lake Mead
Silt-Deposits
Original Bed of Colorado R. Channel
Distribution of Temperature with Depth Lake Mead at Intake-Towers
From Unpublished Data by U.S. Bureau of Reclamation C.C.E. – Los Angeles – 1-13-41

Table 3--Colorado River quality of water-records, in parts per million discharges and analyses from United States Geological Survey data published and unpublished

Year ending September 30	Lake Mead inflow, Colorado River at Grand Canyon runoff		Lake Mead inflow, Grand Canyon analyses			Lake Mead outflow, Willow Beach analyses[a]			Discharge below Boulder
	Million ac-ft	Per cent of normal	Total solids	Total hardness	Noncarb. hardness	Total solids	Total hardness	Noncarb. hardness	Million ac-ft
1926	14.4	92	523	251	121	549[b]	270[b]	(135)[b]	14.3[b]
1927	17.3	111	569	285	152	608[b]	293[b]	(160)[b]	17.0[b]
1928	15.6	100	491	254	121				
1929	19.4	125	555	281	146				
1930	13.4	87	622	311	160				
1931	6.7	44	813	371	206				
1932	16.0	104	531	270	126				
1933	10.0	65	635	311	162				
1934	4.66	31	960	425	256	972[b]	440[b]	273[b]	4.9[b]
1935	10.2	67	560	277	132	693	322	184	5.6[a]
Feb. 1 - Sept. 30, 1935[c]	9.3	....	481	247	116	532	260	135	4.6[a]
1936	12.3	81	591	305	152	596	292	167	6.3[a]
1937	12.4	82	610	310	152	703	359	231	5.8[a]
1938	15.6	103	538	281	126	696	358	232	6.2[a]
1939	9.6	64	662	325	163	712	360	231	8.5[a]
1940	7.4	50	750	357	193	761	389	258	7.7
1941	17.0	114	....	....	....	....	....	....	11.7
Weighted means 1926 to 1940	12.3	80	593.4	295.1	148.7	....	....	....	....
Feb. 1, 1935 to Sept. 30, 1940	11.2	74	594.7	300.9	147.0	677.9	342.5	214.9	6.7[a]
Estimated normals 1926 - depletion	15.6	100	530	265	130	590[d]	280	160	....
1940 - depletion	15.0								

[a] Taken at Willow Beach, 10 miles below Boulder Dam. [b] Taken at Topock, 115 miles below Boulder Dam. [c] Water impounded in Lake Mead from February 1, 1935. [d] Estimated conditions after leaching and flushing of Lake Mead Area.

Note: Data from United States Geological Survey Water-Supply Papers 596, 636, and 638, and unpublished records on file in the Los Angeles office of the Survey.

about 1,000, taken at the dam, with nearly as many more from various locations and depths elsewhere in Lake Mead. The results are much too voluminous and involved to permit satisfactory summarizing in advance of the release of the Density Currents Committee report.

For aqueduct-purposes, however, they show that the effect of subnormal runoff with above-average salinity during the Lake Mead filling-period, combined with evaporation-losses and the leaching action on the desert areas submerged (160,000 acres), was chiefly to increase markedly the dissolved content of calcium sulphate or gypsum in the reservoir-storage and releases, as compared with the average inflow-analyses. Sulphate increased from a previous average of 221 parts per million to about 370 parts per million by March, 1941, then decreased rapidly to less than 300 parts per million for the upper 75 per cent of the storage during the 1941-flood inflow, and period of spill. Chlorides meanwhile increased from an earlier average of 53 parts per million to 80 parts per million in upper strata and nearly 100 parts per million at bottom depths, returning rapidly to normal proportions during the spill as regards upper levels of the reservoir-capacity. This contrast is consistent with the fact that surveys showed only about six acres of actual salt (NaCl) outcrops or salt mixed with soil, whereas several thousand acres were more or less noticeably marked with scattered gypsum-crystals in the Detrital Wash and Virgin River areas.

It has been computed by the United States Bureau of Reclamation that at the end of 1940 the average dissolved solids of the Lake Mead storage-contents would have been 554 parts per million on the basis of analyses of inflow and outflow, if no additional mineral salts had been dissolved from the flooded areas. But depth samples as mentioned show for early in 1941 an average of about 800 parts per million total dissolved solids near Boulder Dam and a weighted average of not

less than 700 parts per million for the entire reservoir during the winter period of 1940-41. The increase ascribable to leaching action in terms of gypsum for simplicity, neglecting minor constituents, is equivalent to about 2,000 acre-feet of crystalline material. Fortunately, this only has to be dissolved and disposed of once, during the first filling of the reservoir, and another season of normal inflow should nearly complete the flushing out of the reservoir. But this makes clearer the reasons for the present temporarily high salinity of aqueduct-water, both raw and treated, as Lake Mathews was filled chiefly in 1940 when Lake Mead releases were worst in salinity, and very little aqueduct-water has since been pumped from the Colorado River. Within two or three years, total dissolved solids of Colorado River aqueduct-water should not exceed 600 parts per million. It may be noted (Fig. 2) that the increase in noncarbonate hardness due to gypsum has in part been offset by a material reduction in carbonate hardness resulting from evaporation and biological action. This is evidenced also by a very noticeable lime-deposit on the reservoir shore-line, especially prominent as seen from a boat during the winter period of falling water-level.

Investigations of Colorado River water-quality will long be continued because of possible harmful effects of Upper Basin irrigation-consumption and drainage-return flow, and of trans-mountain diversions there. The salinity and hardness of the hold-over storage in Lake Mead will undoubtedly increase again unpleasantly, toward the end of the next severe drought-cycle, such as prevailed on the Colorado River from 1930 to 1940, but its repetition may be postponed for a generation or more if wishful thinking on the subject is not entirely in error. For the present, we have the satisfaction that Colorado River water is actually in use, aiding defense activities with a line to supply Camp Hahn at March Field, for example, and relied on for stand-by service as and when needed by the emergency industries and increased population of San Diego as well as of the Los Angeles Region. The water as furnished is of satisfactory quality that will soon show marked improvement, and it is available at a feasible cost, to supplement our local sources of supply.

Metropolitan Water District of Southern California,
Los Angeles, California

RUNOFF-CONDITIONS IN 1940-41 ON THE SOUTH COAST BASIN, CALIFORNIA

H. V. Peterson

Conditions of runoff and rainfall over the South Coast Area of California during the season of 1940-41 were such that the public at large was kept in a state of resigned expectancy. With the memory of the flood of March 1938 still fresh in their minds, people, through the months of February and March, 1941, began noting with growing apprehension the mounting precipitation-figures and the constant and prolonged storms that covered the South Coast Area. Newspapers headlined rainfall as records approached 25-year highs, 40-year highs, and edged toward the all-time recorded high. The layman in this territory, perhaps to a greater extent than elsewhere, instinctively realizes that a continual recurrence of rain is usually an indicator of floods.

The public's apprehension, although their fears were not realized, was not without foundation. At the beginning of the year 1941 the seasonal rainfall, as recorded at the Los Angeles Station, was 150 per cent of mean. January with a rainfall of 2.21 inches was somewhat below normal but the seasonal cumulative total to February 1 was still above. The rainfall during February at Los Angeles, 12.42 inches, was nearly 400 per cent of the February mean, and March with a fall of 8.14 inches was more than 300 per cent of the monthly mean. A series of storms which began on February 6 continued almost uninterruptedly until March 5. The rainfall-data show that during this period there was scarcely a spot in the basin that escaped rain for more than two days in succession. Los Angeles recorded rain of varying amounts on 23 of the 28 days, San Bernardino 16 days, Claremont 18 days, Pasadena 20 days, Pacoima Dam 20 days, and nearly every other station shows a similar record. The recorded rainfall during February and March at the Los Angeles Station was 20.56 inches. The record of rainfall during two months occurred in February and March of 1884 with 25.73 inches, this period being accompanied by an outstanding flood. In 1938 the same two-month record was 17.75. At San Bernardino the rainfall of February and March 1941, was 18.70 inches compared to 22.15 inches in the two-month record of February and March, 1884, and 16.58 in the same two months of 1937-38. It is not surprising therefore that the public showed considerable concern over the prospect of floods.

Despite the prolonged rains, however, the streams of Southern California conducted themselves with admirable concern of the public welfare. It is true in certain localities, particularly in the headwater-drainage of the Los Angeles River in the western part of San Fernando Valley, flooding occurred and some damage was reported but over the area as a whole the streams did not reach

Table 1--Maximum daily discharge during seasons of high runoff, South Coastal Basin, California

Stream	Discharge for season of									
	1913-14		1915-16		1921-22		1937-38		1940-41	
	Sec-ft	Date	Sec-ft	Date	Sec-ft	Date	Sec-ft	Date	Sec-ft	Date
Santa Ana near Mentone	2,240	2-21	....	....	1,700	12-20	15,500	3-2	1,180	12-24
Waterman Canyon near San Bernardino	175	2-21	....	....	87	1-2	478	3-2	63	2-21
Lytle Creek near San Bernardino	....	....	4,750	1-18	....	....	8,960	3-2	594	3-4
San Antonio near Upland	607	2-21	....	....	498	12-20	4,110	3-2	157	3-13
San Gabriel near Azusa	11,800	2-20	22,300	1-18	16,000	12-19	21,660	3-3	....	....
Santa Anita near Sierra Madra	....	....	....	....	355	12-20	1,580	3-2	235	3-4
Arroyo Seco near Pasadena	3,690	2-20	....	....	1,020	12-19	2,700	3-2	725	2-20
Big Tujunga near Sunland	....	....	....	....	2,500	12-19	13,000	3-2	1,260	2-21

flood-stage. Table 1 shows the maximum mean daily discharge recorded on eight representative streams in the district during four outstanding flood-seasons together with the season of 1940-41. The streams considered are Santa Ana River at Mentone, Waterman Canyon, Lytle Creek, San Antonio Creek, San Gabriel River near Azusa, Santa Anita Creek, Arroyo Seco Creek, and Big Tujunga Creek. The seasons listed are 1913-14, 1915-16, 1921-22, 1937-38, and 1940-41. Not all the records are complete, some of the streams were not measured during the early seasons and unfortunately the great floods of 1915-16 and 1937-38 destroyed or incapacitated many of the gaging-stations so that no records of peak-discharges were obtained. In many cases the peaks given represent estimates only. The records of 1940-41 are unpublished, and, although fairly complete are provisional and subject to change.

Significant contrasts are at once apparent. In general, the maximum mean daily discharges on representative streams in the South Coast Area in 1940-41 were less than one-tenth as great as those occurring in 1937-38 and in the main considerably less than in other outstanding flood-years. Unfortunately no comparative records are available for streams in the extreme western part of the San Fernando Valley where flood-conditions did prevail at times during the season of 1940-41.

Only a few data are available on maximum peak-discharges which occurred during the various flood-years, but these also show a significant contrast. The peak-discharge on the Santa Ana in 1940-41 was 3,080 s-f compared to an estimated 52,300 s-f in 1938 and 2,130 s-f in December 1921. On Santa Anita Creek the peak-flow in 1940-41 was 465 s-f compared to 5,200 s-f in 1938 and 781 s-f in 1931. On Arroyo Seco the maximum flow in 1940-41 was 1,340 s-f compared to 8,620 in 1938, 2,800 in 1921, and 5,630 in 1914. The maximum on Waterman Canyon during 1940-41 was 190 s-f compared to 2,350 s-f in 1938. The peak-discharge of the San Gabriel at Azusa for 1940-41 is not available but it is apparent that it was no more than a small fraction of that which occurred in 1938, estimated at 65,700 flowing over Morris Dam, or in 1916, estimated at 40,000 s-f.

The general lack of stream-discharges approaching flood-stages during the season of 1940-41 can be attributed to three general factors, namely, (1) an almost ideal distribution of rain from the standpoint of water-retention during the major storms of the season, (2) a lack of high-intensity storms or excessive rainfall occurring within a short period of one or two days or less, (3) the absence of heavy snow in the mountain area. In addition, it may be pointed out rainfall in the mountain regions was not as proportionately high in relation to the long-term record as in the valley-areas. In other words, while the valley-stations recorded a rainfall during the season of 1940-41 considerably in excess of that occurring in other seasons of high runoff, the precipitation at most of the mountain stations was in general below that of the seasons of 1937-38 and 1915-16.

Table 2 is a summary of the outstanding storms which produced the major runoff during the five seasons already noted. A comparison of the storm-rainfall for the five seasons indicates

that the storm of February and March, 1941, was one of the greatest of the group in regard to total rainfall. The outstanding characteristic of the storm, and the one for which the residents of Southern California should be duly grateful, is the fact that it extended over a period of 28 days with a more or less even distribution of rain throughout the entire period. The storm of 1938 was limited to five days with much of the rain concentrated in one or two days. The flood-producing storms of 1913-14 and 1921-22 were likewise confined to comparatively short periods.

A comparison of the maximum day's rain in 1941 and 1938 reveals to a marked degree the contrast in the storm-characteristics. The comparison is shown in Table 3, and it will be noted that the maximum of 1940-41 is invariably lower--in many cases less than one-half the daily maxima of 1937-38.

Table 2--Comparison of storm-precipitation at rainfall-stations located in South Coastal Basin, California

Station	Storm-precipitation during period of maximum runoff											
	1913-14			1915-16		1921-22			1937-38		1940-41	
	Precipitation			Precipitation		Precipitation			Precipitation		Precipitation	
	In.	No. days	Max. days	In.	No. days	Max. days	In.	No. days	Max. days	In.	No. days	Max. days	In.	No. days	Max. days
Bear Valley Dam	10.83	4	3.65	.....	...	.....	24.30	6	7.50	26.95	5	15.06	20.20	19	2.97
Seven Oaks	9.10	5	3.00	31.87	20	6.10	26.98	13	6.35	18.32	5	8.47	10.77	14	2.26
San Bernardino	4.71	5	1.81	17.37	22	5.29	13.43	14	2.84	10.05	5	4.46	14.27	16	3.42
Squirrel Inn	16.29	5	5.23	54.47	24	16.81	37.96	13	8.55	26.17	5	10.97	25.18	19	5.85
Lytle Creek	.....	..	.....	.....	...	.....	26.19	13	6.04	.....	...	.....	18.04	19	2.92
Camp Baldy	.....	..	.....	.....	...	.....	39.07	14	10.65	33.23	5	12.00	21.02	17	4.12
Claremont	.....	..	.....	18.74	20	4.68	12.30	11	2.88	9.99	5	5.73	14.65	18	2.66
Opids Camp	10.92	5	5.53	.....	...	.....	.....	...	.....	27.27	5	14.92	36.42	18	7.45
Azusa	11.84	4	6.95	20.78	21	4.76	.....	...	.....	13.44	5	6.72	16.14	23	3.36
Mt. Wilson	.....	..	.....	.....	...	.....	34.80	13	11.00	26.23	5	11.83	33.47	18	6.60
Pasadena	11.44	4	5.27	17.14	21	4.68	15.20	13	3.36	14.81	5	7.70	22.63	20	4.36
Los Angeles	7.04	4	4.26	14.05	21	4.16	9.37	12	2.12	11.06	5	5.88	15.85	23	2.78
Pacoima Dam	.....	..	.....	.....	...	.....	14.98	9	3.75	11.48	5	5.38	16.85	20	2.37
Storm-period	Feb. 17-22			Dec. 29-Jan. 30		Dec. 17-Jan. 3			Feb. 27-Mar. 3		Feb. 6-Mar. 5				

Not only was the rainfall well scattered throughout the storm-period of 1941 but the intensities were comparatively light throughout the year. Several automatic rain-gages were in operation during the period, both at mountain and valley stations. A study of the major storm-periods shows that only at rare intervals during the year were intensities of as much as an inch an hour recorded at stations within the district. Some of the highest recorded intensities of the year, according to available records, are as follows: Camp Baldy, 0.92 inch in one hour and 1.68 inches in three hours; Opids Camp in San Gabriel Basin, 1.27 inches in one hour and 1.87 inches in three hours; Mt. Wilson, 2.15 inches in three hours; Burbank (Airport), 1.13 inches in one hour; Los Angeles, 0.99 inch in one hour and 1.07 inches in three hours. During a large portion of the storm-period the intensities of all other stations were considerably below those given.

Comparative intensities during the flood-producing storms of other seasons are not available but even a glance at some of the daily rainfall-figures indicates that intensities far in excess of those common to 1940-41 must have occurred.

Rain falling on snow-fields does not always produce excessive runoff-conditions, but it is well known that several of the major floods in the South Coastal Basin have been generated by a concurrence of rain following on ripe snow during a period of abnormal thawing temperature. This condition was prevalent to some extent during the season of 1921-22, and, although no direct measurements are available, it appears to be well established that the great floods of 1862 were in part due to heavy rains falling on deep snow-packs. The fact that no significant accumulations of snow occurred during the season of 1940-41 contributed in some measure to the low peak-discharges in the streams.

Although the peak-discharges of the streams during the season of 1940-41 were

Table 3--Comparison of maximum daily precipitation at rainfall stations located in South Coastal Basin, California, for seasons of 1937-38 and 1940-41

Station	Maximum daily precipitation in inches	
	1937-38	1940-41
Mountain		
Bear Valley Dam	15.06	2.97
Seven Oaks	8.47	2.99
Squirrel Inn	10.97	5.85
Camp Baldy	12.00	4.12
Opids Camp	14.92	7.45
Mt. Wilson	11.83	6.60
Valley		
San Bernardino	4.46	3.42
Claremont	5.73	2.66
Los Angeles	5.88	1.95

Table 4--Comparison of annual and maximum monthly discharge of south coastal streams, California, during seasons of high runoff

Stream	Annual runoff in acre-feet					Maximum monthly runoff in acre-feet				
	1913-14	1915-16	1921-22	1937-38	1940-41	1913-14	1915-16	1921-22	1937-38	1940-41
Santa Ana near Mentone	78,000	Inc.	165,000	169,140	86,280	15,300	.....	27,500	86,400	14,390
Waterman Canyon near San Bernardino	6,020	Inc.	6,420	5,920	5,100	1,770	.....	1,240	3,510	1,480
Lytle Creek near San Bernardino	47,700+	80,400	.....	103,900	74,120	.....	40,000	.....	48,280	15,300
San Antonio near Upland	25,500	.....	53,300	43,880	38,850	9,330	.....	9,900	21,060	7,800
San Gabriel near Azusa	296,000	279,000	410,000	353,300	319,000	121,000	148,000	119,000	220,380	97,000
Santa Anita near Sierra Madre	.....	.....	16,600	15,500	14,130	.....	.....	4,390	9,670	4,500
Arroyo Seco near Pasadena	33,000	.....	25,400	21,870	25,210	19,100	.....	8,120	14,420	8,150
Big Tujunga near Sunland	.....	.....	103,000	83,960	75,930	.....	.....	25,900	60,540	24,840

comparatively small, having been exceeded many times in the past, the seasonal runoff has been exceeded but few times since stream-measurements began. Table 4 shows the seasonal runoff and the maximum monthly runoff of the eight representative streams already noted during the five seasons previously listed. Comparison between the runoff of 1940-41 and that of other seasons shows the following general relationship. The runoff of 1940-41 of the Santa Ana River at Mentone has been exceeded several times in the past, but runoff from the San Gabriel River during the season was the fourth highest on record since measurements began in 1896, being exceeded only in 1921-22, 1937-38, and 1906-07; On Lytle Creek the runoff of 1940-41 was the third highest since records began in 1904-05, being exceeded only in 1915-16 and in 1937-38. (No measurements were taken on Lytle Creek in 1921-22.) Most of the other streams assume a similar position in the scale of runoff, the season of 1940-41 usually being exceeded by the runoff in 1937-38 and 1921-22. In Arroyo Seco the runoff during 1940-41 of 25,210 was second highest on record since 1913, being exceeded only by the flow of 33,300 in 1913-14.

So far as maximum monthly runoff on the various streams is concerned, the discharges of 1940-41 are, with one or two exceptions, the lowest during any of the five seasons considered. The maximum month on the Santa Ana River at Mentone for the season of 1940-41 was April with a runoff of 14,390 acre-feet. This compares with 86,400 in March of 1938, 27,500 in May of 1922, and 18,900 in May of 1914. The monthly maximum during 1941 on Lytle Creek occurred in May with 8,950 acre-feet, compared to 46,230 in March of 1938, 40,000 in January of 1916, and 9,220 in

March of 1914. The monthly maximum during 1940-41 on the San Gabriel River was 97,000 in March compared to 220,000 in March of 1938, 148,000 in January of 1916, 121,000 in February 1914, and 119,000 in December of 1922.

It is interesting to note that in many seasons maximum monthly runoff did not coincide with maximum monthly rainfall. Moreover, in three of the seasons under consideration the maximum monthly discharges recorded on the eight streams did not occur in the same month but were scattered anywhere from early winter to late spring. The outstanding storms which occurred in January, 1916, and March, 1938, were apparently among the few that were sufficiently widespread and of the type to cause all streams in the area to peak at approximately the same time. The coincidental arrival of such peaks on the valley-floor is, of course, largely responsible for extreme flood-conditions.

The anomaly of relatively low peak-discharges, low maximum monthly runoff, and high seasonal runoff during the season of 1940-41 can be attributed to the very favorable distribution of rainfall already mentioned coupled with the somewhat unique geologic features of the drainage-basins. To those not acquainted with characteristics of drainage-basins in Southern California it may seem difficult to understand how a 20-inch rainfall occurring with a period of from 20 to 28 days, even though such rain was well distributed, could fail to produce discharges far in excess of those recorded. To take a specific example, about 18 inches of rain, or 180,000 acre-feet of water, fell on the 189 square miles, comprising the Santa Ana Basin above Mentone, during the 28-day storms of February and March. From February 6 to March 5 the runoff from this same area was only 9,600 acre-feet. Allowing three inches of rain for evaporation, transpiration- and interception-losses, and assuming that some storage took place in the Bear Valley Reservoir, there still remained about 150,000 acre-feet unaccounted for. This quantity must have been retained as ground-storage, a retention of slightly less than 15 inches for this one storm. Add to this the retention from previous storms and one obtains an idea of the absorptive capacity of the mountain area. Other drainage-basins in the area show retention-capacities as great or greater than the Santa Ana.

Extremely fractured and shattered bedrock consisting in the main of fine to coarsely crystalline igneous rock, together with small amounts of medium to coarse-textured sedimentary formations, underlies practically all of the basins draining from the San Bernardino and San Gabriel Mountains. This material has disintegrated in most localities to form a coarse, porous soil-mantle. The porous soil-covering coupled with the underlying shattered bedrock forms a surface-storage capable of retaining the large quantities of water indicated for more or less protracted periods. The amount of rainfall entering this ground-storage space is of course dependent to a large extent on storm-intensities together with other complex factors, such as antecedent rainfall, slope, and vegetal covering. The release from ground-storage is likewise dependent on a number of complex factors, many of which are difficult to evaluate.

In regard to the retention-characteristics of drainage-basins it may be pointed out that of the streams which reached flood-stage and caused noteworthy damage during the season of 1940-41 most are underlain by fine-textured sedimentary rocks and have soils that are less favorable to the absorption of rainfall than drainage-basins located in the San Bernardino or San Gabriel Mountains. The streams as already noted are located principally in the western part of San Fernando Valley and drain from the Santa Suzunna Mountains and Simi Hills. However, this ground-condition may not be entirely responsible for the increased runoff since rainfall-intensities may have been higher in this area than over the region to the east. No records of rainfall-intensity in the district are available.

As previously noted, rainfall on the valley-floor during 1940-41 was one of the highest on record, being exceeded in general only by the record year of 1883-84. From one of the few records available on a stream draining strictly from the valley-floor and not influenced by mountain terrain, it appears that valley-runoff was also one of the highest. San Jose Creek, which drains an area along the east side of Los Angeles County in the vicinity of Pomona and Puente, has a record extending from 1929 to the present. The runoff during 1940-41 of 22,730 acre-feet is almost one and one-half times that of the next highest measured runoff occurring in 1937-38, 15,450 acre-feet. The third highest recorded runoff, 9,600 acre-feet, occurred in 1936-37. When it is considered that the probable maximum valley rainfall-intensity during the season of 1940-41 was considerably less than at the rate of one inch per hour and that the terrain of this basin is, for the most part, flat or gently sloping, the runoff in comparison to that of 1937-38 is somewhat unexpected. It would appear that the recurrence of rains over the 28-day period saturated the surface-soils, in places at least, causing relatively high direct flood-runoff. It may be noted in this regard that 75 per cent of the seasonal runoff occurred on San Jose Creek during the months of February

and March. Eighty per cent of the yearly runoff in 1937-38 took place within six or seven days following the storm of March 2.

A study of the entire disposition of rainfall on the valley-floor in comparison with mountain drainage presents an interesting analysis. The runoff of San Jose Creek during the maximum months of February and March, 1941, was 17,000 acre-feet, which represents a little less than four inches over the drainage-area, an amount that on a square mile basis is almost two and one-half times greater than the discharge from the Santa Ana Basin above Mentone during the same period. Subsequent runoff of San Jose Creek during the remainder of the season was 3,490 acre-feet, which is less than an inch of water over the contributing area, whereas on the Santa Ana River the subsequent runoff during the same period was 51,000 acre-feet or more than five inches. How much of the rainfall going into ground-storage on the valley-floor was lost by evaporation and how much percolated to the ground-water level is impossible to determine, but it is at once apparent that so far as surface-runoff is concerned the valley-areas furnish much less from ground-storage than do the mountain areas. Again geology is probably the controlling factor in this condition.

In conclusion, it may be said that from the standpoint of rainfall and runoff the season of 1940-41 was one of the most interesting on record. It is almost unique for in few other seasons wherein the rainfall approached that recorded in 1940-41 did the South Coastal Basin escape widespread or destructive floods. The runoff was great, yet in practically all cases the discharges were small enough to be safely and efficiently handled. Hydrologists and geologists alike will find much of interest in a study of the behavior of the streams. It is probable that a great number of years will elapse before the area experiences another such ideal season.

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CHANGES IN GROUND-WATER ELEVATIONS OF THE SOUTH COASTAL BASIN DURING THE PAST QUARTER-CENTURY IN COMPARISON TO LONG-TIME MEAN PRECIPITATION AND RUNOFF

George B. Gleason

In the bulletins of the California State Division of Water Resources dealing with the various phenomena occurring within the area, South Coastal Basin is defined as the drainage-areas of the Los Angeles, San Gabriel, and Santa Ana rivers, together with areas draining directly to the ocean between Topanga Canyon and San Joaquin Hills, as delimited on the key map of Figure 1.

The area includes the south slope of San Gabriel and San Bernardino Mountains, an intermediate range of lower mountains and hills roughly paralleling them extending between the Santa Monica and Santa Ana Mountains, and valley-lands lying between the two ranges and between the lower range and the ocean. The mountains and hills are shown cross-hatched on the map and the valley-lands left unshaded. Within these alluvial valleys lie the several ground-water basins bounded and named on the map, which are here discussed. While the basin-boundaries shown enclose also the tributary nonwater-bearing mountain and hill areas, the ground-water basins themselves are here considered to include only the alluvial water-bearing masses.

Some of the boundaries form a distinct barrier to the movement of ground-water across them; others impede the flow but do not stop it; others are hydrographic divides whose positions may vary and which stop the flow only because water moves in the direction of its steepest slope. Still others are arbitrary and are placed as they are for convenience only. Within the basins themselves as here delimited there is wide variation in the character of the alluvium, so ground-water moves both horizontally and vertically more easily in one part of the basin than in another.

It is the purpose of this paper to present graphically records of water-table fluctuation at wells located in these ground-water basins and to discuss briefly some of the factors involved in drawing conclusions from the records. A detailed evaluation of the factors and the drawing of final conclusions is outside the scope of the paper.

San Gabriel Basin--With the exception of the eastern boundary along the Glendora and the San Dimas group of sub-basins, and that established arbitrarily across the westerly end of San Jose Valley, the boundaries of San Gabriel Basin are well defined. Raymond Fault, while perhaps not

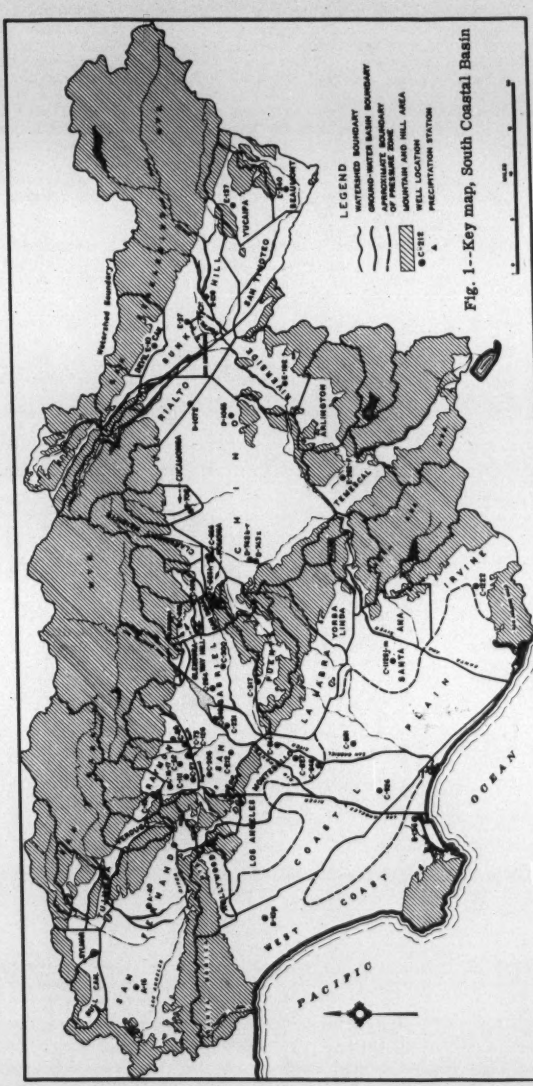


Fig. 1.--Key map, South Coastal Basin

so impervious as are the mountains and hills, is still a distinct barrier to underflow as is indicated by the wide difference in elevation of the water-table above and below the fault-zone. The two basins shown at the mouth of San Gabriel Canyon, not named on the map, while separated from the Main Basin by faults, are so operated that they may well be treated as a part of the Main Basin. They fill virtually every year and nearly all the water pumped from them is applied on the basin below.

Excepting for relatively narrow zones along the extreme west and east boundaries and an area south of and extending along about the middle third of Raymond Fault, the water-bearing material is open, the wells are good producers and ground-water moves with relative freedom from one point to another in the basin. The material becomes finer and more uniformly graded with distance from the mountains and in a zone extending two or three miles above Whittier Narrows there is some artesian pressure.

The mountain inflow available to the area is large, the principal source being the San Gabriel River, with smaller contributions coming from mountain streams between Eaton and San Dimas creeks. Virtually all of the outflow, both surface and underground, passes out through the narrow and shallow constriction at Whittier Narrows.

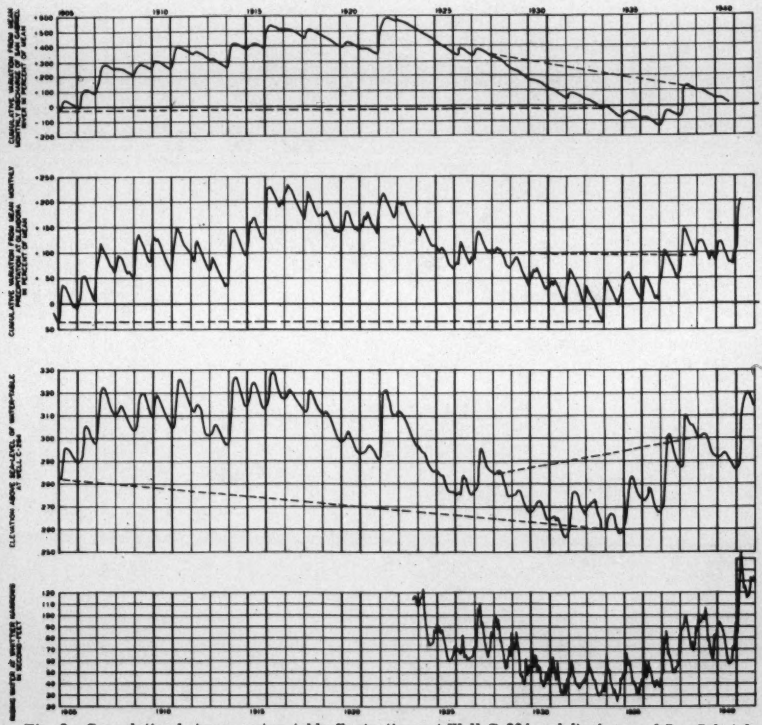


Fig. 2--Correlation between water-table fluctuations at Well C-294 and discharge of San Gabriel River, precipitation at Glendora, and rising water at Whittier Narrows

A study of records of precipitation extending back to 1872 shows there has been wide variation in the amount of precipitation both as regards individual years and periods several years in length. Two complete cycles (the term is not here used in its strict mathematical sense) are encompassed in that period, and the later one, 29 years in length and extending from 1904-05 to 1932-33, has average precipitation not far different from that of both periods. For purposes of this discussion it is assumed that this 29-year period is one of long-time mean precipitation.

While the relation between rainfall and discharge from the mountains is not particularly close for individual years, it is probable that factors which control the runoff, other than rainfall, balance out during a period of this length and it is, therefore, further assumed that the average during the 29-year period is the long-time mean discharge.

The cumulative variation diagrams for discharge of San Gabriel River and precipitation at Glendora, shown on Figure 2, are so constructed that the straight line connecting points on the diagram at the two ends of the 29-year period adopted as one of mean stream-discharge and precipitation, is horizontal. It follows that any two points on the diagram which lie on a horizontal line delimit a period of long-time mean discharge or precipitation.

As shown by the diagram, the 11-year period, 1927-28 to 1937-38, is one of very nearly long-time mean precipitation. While the downward slope of the line on the discharge-diagram shows that the period was one of less than mean inflow from the mountains, the behavior of wells during that period is still useful as a base from which to estimate what might be expected to occur in a longer period or under different conditions.

Fluctuations of the water-table result from variations in the supply to and extractions from the ground-water. Nearly all the natural supply consists of percolation from streams and from precipitation on the surface. It takes some time for this percolate to reach the water-table after it leaves the ground-surface, so there is probably considerable variation in the amount in transit following wet and dry years. The 11-year period was preceded by and ended with two wet years so the amount in transit was probably about equal at the beginning and end of the period. This being true, it is probable that change in storage below the water-table as indicated by water-level measurements at wells during the period is not far from the total change both above and below the water-table.

There is a large amount of pertinent hydrologic information available during this period and that, of course, adds to its usefulness as a base.

It is interesting to note on Figure 2 that, both as regards fluctuation from month to month and over long periods, the elevation of water-table at the well generally follows the precipitation diagram more closely than it does that of stream-discharge. This does not mean that mountain inflow has no effect on the water-table elevation. In fact, it is probably true that the supply in dry years originates largely in that source. In wet years a relatively large part comes from precipitation. Rises in the water-table occur at times when both stream-flow and precipitation are effective and the extractions are small. Drops occur when there is little precipitation, when most of the stream-flow is being diverted for direct use, and extractions are large. Each of these factors contributes to the fluctuation of the water-table to a varying degree. Whatever the effect of each may be, the fact remains that the cumulative variation from mean precipitation-diagram and the graph showing fluctuation of water-table at Well C-294, all shown on Figure 2, do follow one another quite closely.

As the ground-water in San Gabriel Basin moves downward from the mountains toward the ocean, the constriction at Whittier Narrows so impedes the flow that the water-table rises until it stands at an elevation higher than the bottoms of the stream-channels. This results in rising water in the channels and the ground-water stream becomes in part a surface-stream.

The diagram on Figure 2 shows the variation in amount of this surface-flow. The variation from year to year is largely due to changes in elevation of the water-table. Variations within the year, however, are due more to changes in consumptive use in the area of high water-table where the rising water originates. High points on the graph of rising water occur during months of low consumption and low points during the hot summer months. The graph shows only the measurable surface-flow and does not include the water extracted by vegetation in the area of high water-table.

The diagram presented on Figure 3 shows the relationship between water-table elevation at Well C-294 near Baldwin Park and the average annual rising water in the streams at Whittier

Narrows. The records of rising water for the years 1921-22 and 1922-23 are not very dependable and are not given much weight.

It is notable that from 1934-35 to 1937-38 the points depart farther and farther from the straight line which approximates the relationship prior to that time. Following 1937-38, the points gradually approach the line again.

Just what this indicates is subject to question. There may be a lag following an abrupt rise in the water-table or it may be that control of the river following the construction of Morris Reservoir and the dams of the Los Angeles County Flood-Control District with attendant spreading operations may have changed the relationship between elevation of the water-table at Well C-294 and that immediately above the Narrows upon which depends the amount of rising water.

To avoid confusion and conserve space the graphs of wells shown on Figure 4 while arranged generally in order of their elevations are not plotted on an elevation-scale and do not indicate differences in elevation as between the different wells. They do, however, show the fluctuations at each.

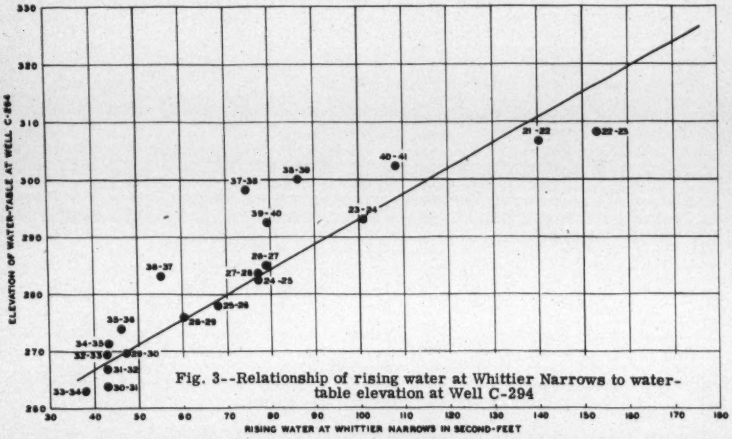


Fig. 3--Relationship of rising water at Whittier Narrows to water-table elevation at Well C-294

Wells C-294 near Baldwin Park and C-249 at the upper end of El Monte Island, are near the center of the basin. Both show relatively large fluctuations, those at C-249 which lies closer to the river being somewhat larger in the wet years. Well C-231, at El Monte, being close to the upper edge of the area of rising water, has fluctuated much less.

In the westerly portion of the basin, Well C-206 at Alhambra even though far back from the rising-water area shows small fluctuations, with C-212 near Wilmar, as is to be expected, fluctuating still less.

In the easterly portion Well C-300 in West Covina while not changing so much as wells C-294 and C-249 nearer the river, does fluctuate quite widely. At Well C-317, located near Puente, the fluctuations are again smaller and more uniform.

At all of these wells, the water-table dropped during the 29-year period of average supply. During the later 11-year period it rose in the central and upper eastern portion of the basin (wells C-294, C-249, C-231, and C-300), remained about level at Puente, and dropped in the westerly portion (C-206 and C-212).

These drops and rises indicate in a general way that without artificial control of the river and with net artificial and natural extractions from the ground-water both as they were during the

29-year period, a small overdraft existed. During the 11-year period, however, with the river partially controlled and with net extractions as they were at that time, there was an excess in all save the westerly portion of the basin. This excess, if continued, must eventually cause an increase in the rising water and natural extractions above Whittier Narrows.

The continued drop at Well C-206 in Alhambra and the small fluctuation there indicate that if any water from other portions of the basin reaches this westerly part, its arrival must be long delayed. If the drop continues, however, water will eventually enter from the east or southeast.

The graphs shown on Figure 5 are some of those shown on the preceding Figure but are replotted on actual elevation scale to bring out two interesting points. First, the water-table at Well C-317, which is located near Puente at the point where San Jose Valley joins San Gabriel Basin, generally stands higher than that at Well C-294 which is much nearer the river and approximately five miles farther north toward the mountains. This indicates that a considerable portion

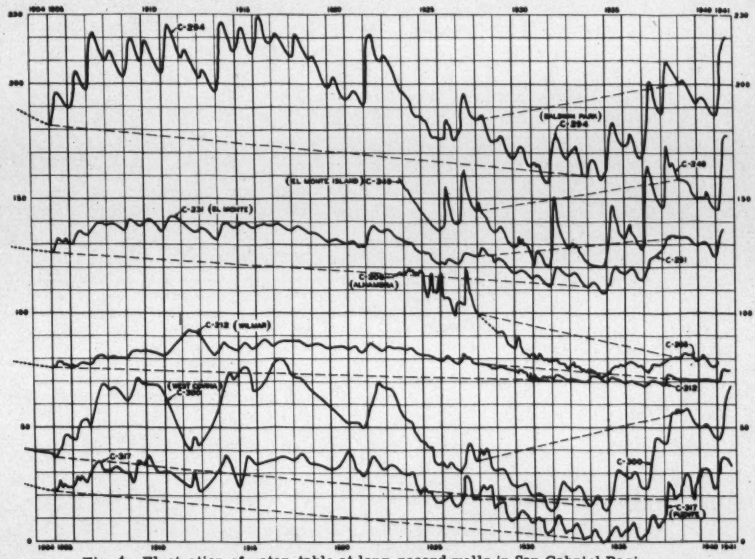


Fig. 4--Fluctuation of water-table at long-record wells in San Gabriel Basin

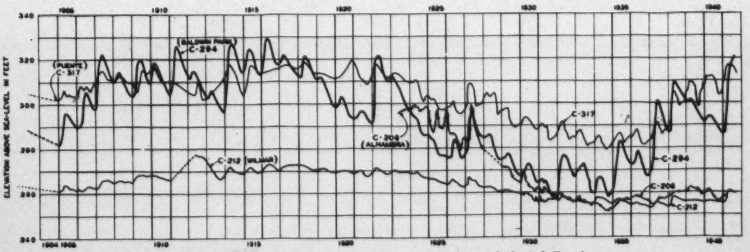


Fig. 5--Comparative elevation at wells in San Gabriel Basin

of the water reaching the water-table at Well C-317 does not come directly from San Gabriel River and probably in a large measure comes from rainfall on the surface.

At the other side of San Gabriel Basin it is notable that the water in Well C-206, in the northern portion of Alhambra, always stands very little higher than that in Well C-212 about four miles closer to the Narrows in the direction of ground-water flow. Many ground-water contour-maps drawn in the past show a pronounced valley in the water-table underneath Alhambra and San Gabriel with a ridge or mound of water lying just to the east. The westerly portion of this mound lies in the zone of dense material south of the middle third of Raymond Fault. It seems probable that any water moving westerly from San Gabriel River would have to enter from the southeast. At present, the configuration of the water-table is such that this does not occur.

Raymond Basin Area.--The external boundaries of Raymond Basin Area are well defined. Hills and mountains surround the area except across narrow La Canada Valley on the northwest and Raymond Fault on the south. Although some ground-water no doubt passes this fault, its amount is small. The map of Figure 1 shows this basin divided into three parts. That on the northwest is known as Monk Hill Basin and that on the east as Santa Anita Sub-Area. The portion between is called Pasadena Sub-Area. The boundary between Monk Hill Basin and Pasadena Sub-Area, while arbitrary through a portion of its length, constitutes a barrier to the free movement of ground-water and holds the water-table much higher on its upstream side. The boundary between Pasadena and Santa Anita sub-areas is an arbitrary line lying within a zone of rather dense material on either side of which the water-table is at about the same elevation.

The principal source of mountain water to Raymond Basin Area is Arroyo Seco, not only because it is the largest stream, but also because Devils Gate Reservoir, in the past, has held back the flow, permitting much more of it to percolate than would have under natural conditions. Eaton Creek has also contributed some water but percolation from that stream above Raymond Fault, has not been large.

The ground-water stream which flows out of Monk Hill Basin and across Pasadena Sub-Area, moves almost directly east through all the lower portion of its length.

As shown on Figure 6, the water-table over the whole area dropped during the 29-year period, 1904-05 to 1932-33, but because of rapidly changing conditions of culture, it is believed that fluctuations during the 11-year period, 1927-28 to 1937-38, are more significant. During that period the water-table at Well C-10 in Monk Hill Basin rose a little. Just below Monk Hill at Well C-16 it dropped a small amount and farther east at wells C-52, C-73, C-86, and C-122 it dropped more. At Well C-52 the 11-year average drop was greater than that during the 29-year period. Detailed studies indicate that this drop represents an annual average overdraft of about 6,000 acre-feet in the entire Basin with imports and net extractions as they were during the 11-year period.

As already stated, the principal ground-water stream flows south out of Monk Hill Basin to the vicinity of Well C-16, then turns east past C-52, C-73, and C-86. From the study of other wells not shown on the Figure, it appears that in a considerable area around Well C-16 the water moves with comparative ease. Between this area and Well C-52, the water-table slopes steeply and this together with the great difference in rise at Well C-16 and at Well C-52 since 1931 indicates a zone somewhere between the wells, in which movement of ground-water is slow. East of Well C-52, fluctuations at all points of measurement are very much alike, indicating that water there moves horizontally with comparative ease. However, the uniform fluctuations without regard to the wetness or dryness of the year, not only in wells C-52, C-73, and C-86, but in many other wells in the area, indicate that water reaching the central and eastern portion of Pasadena Sub-Area, whether it enters as ground-water from adjoining areas or as percolation from the surface, is regulated in its passage through the alluvium before reaching the ground-water in this portion of the basin.

The slightly greater rise since 1936 at Well C-86, east of Eaton Wash, may indicate that there is some percolation from that stream moving in an easterly direction or it may mean that underflow from the north increased since that time.

The rise at Well C-27, since 1933, might indicate that water moves straight south from C-16 with comparative ease. If this is true, however, the channel through which it moves must be narrow, otherwise Well C-111, which is nearer to C-16, would be affected first and to a greater instead of a lesser degree.

Well C-122 lies in the pressure-zone extending along and just north of Raymond Fault, and

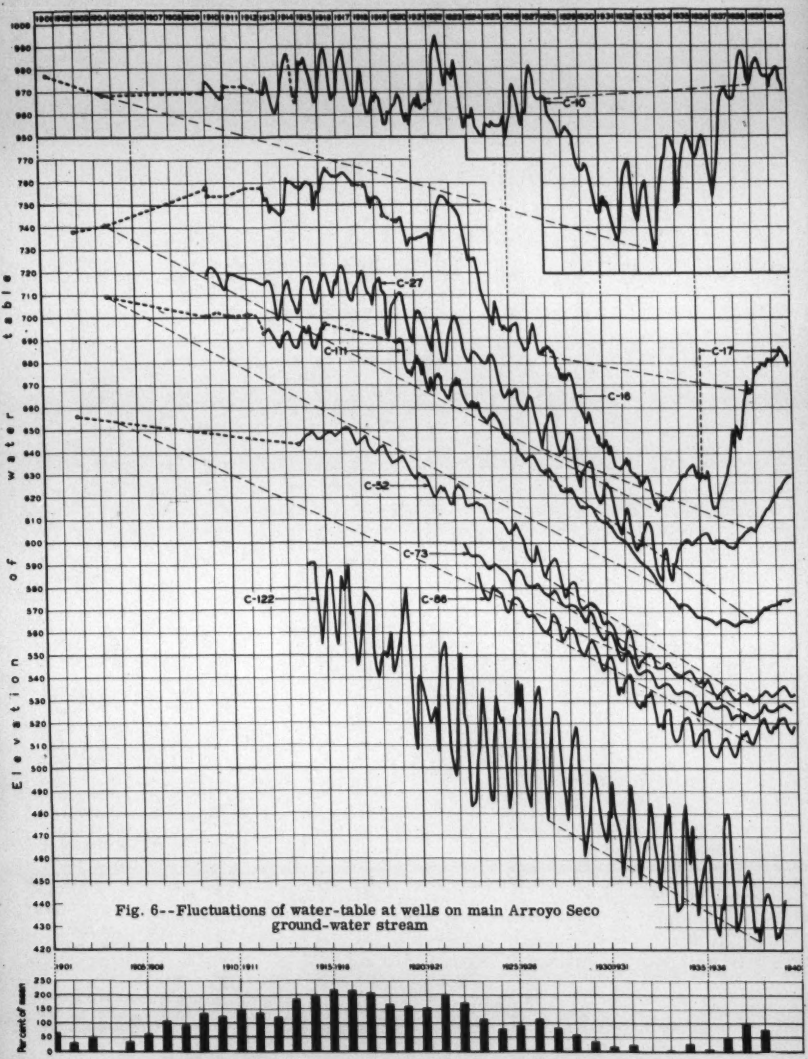


Fig. 6--Fluctuations of water-table at wells on main Arroyo Seco ground-water stream

shows the wide fluctuations typical of pressure-wells in heavily pumped areas. It is noteworthy too that the drop during the 11-year period at that well has been about the same as that at Well C-73, about one-half mile north of it and with a very steep water-table between the two. No conclusive explanation for this phenomenon has been reached.

Figure 6 was prepared by the Division of Water Resources for a different purpose and the method of showing accumulated departure from mean rainfall is different from that used elsewhere in this paper.

Glendora and Way Hill basins--To the east of San Gabriel Basin and draining into it are Glendora, Way Hill, and San Dimas basins. Long-record wells are available in the first two of these and their graphs are shown on Figure 7. On all save their western side, the boundaries of these basins are well defined. There the boundary is to some extent arbitrary, a zone of relatively dense material, in which the water-table slopes steeply extending some distance west into San Gabriel Basin.

As is typical of smaller basins bordering the mountains, the materials comprising the fill

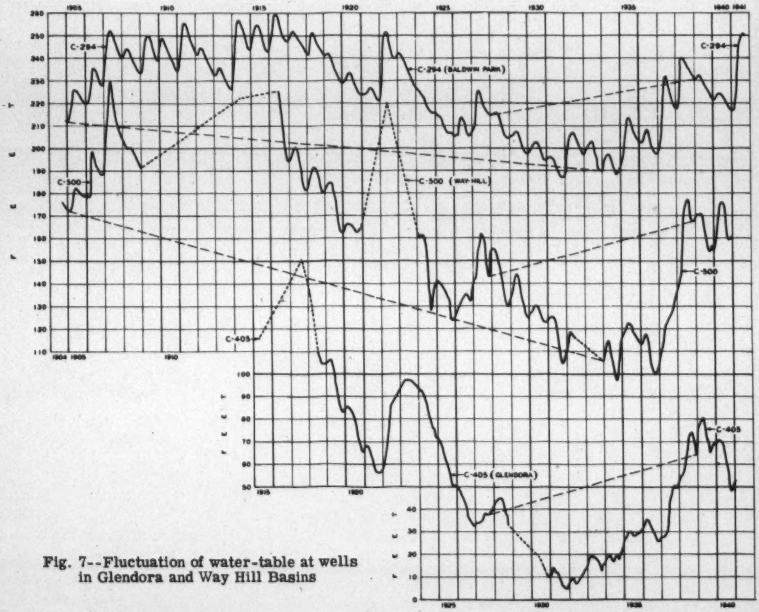


Fig. 7--Fluctuation of water-table at wells in Glendora and Way Hill Basins

contain relatively large amounts of clay and the formation is irregular. Big and Little Dalton creeks contribute mountain water to Glendora Basin and San Dimas Wash flows across Way Hill Basin. On Figure 7 again the scale shows only fluctuations in each well and does not indicate relative elevation as between wells.

In comparison with Well C-294 in San Gabriel Basin, both Well C-500 in Way Hill Basin and C-405 in Glendora Basin fluctuate widely. This is typical of smaller basins from which the extractions are relatively large.

During the 29-year period, the drop in water-table at Well C-500 was large. It may be assumed that the same was true at Well C-405. During the 11-year period both wells showed a rise. This reversal may be due to one or more of several phenomena. First, the lower water-table may have resulted in less outflow underground across the lower boundary; second, water is now imported to Glendora Basin from San Gabriel Basin; and third, conservation measures have probably resulted in the addition of more supply to the ground-water than it received during the earlier period. Whatever the reason, there is no indication of an overdraft in either basin under present conditions.

Hydrologic relationships along Santa Ana River--Diagrams presented on Figure 8 show cumulative variation from 29-year mean discharge of Santa Ana River at the mouth of the canyon, cumulative variation from 29-year mean precipitation at San Bernardino and, for comparison, that at Glendora, fluctuations of the water-table at Well E-37 in San Bernardino, and rising water in Warm Creek above Bunker Hill Dike and in Santa Ana River at Prado. The general principles involved have already been discussed in connection with San Gabriel Basin.

As shown by the diagram, the regimen of precipitation at San Bernardino is somewhat

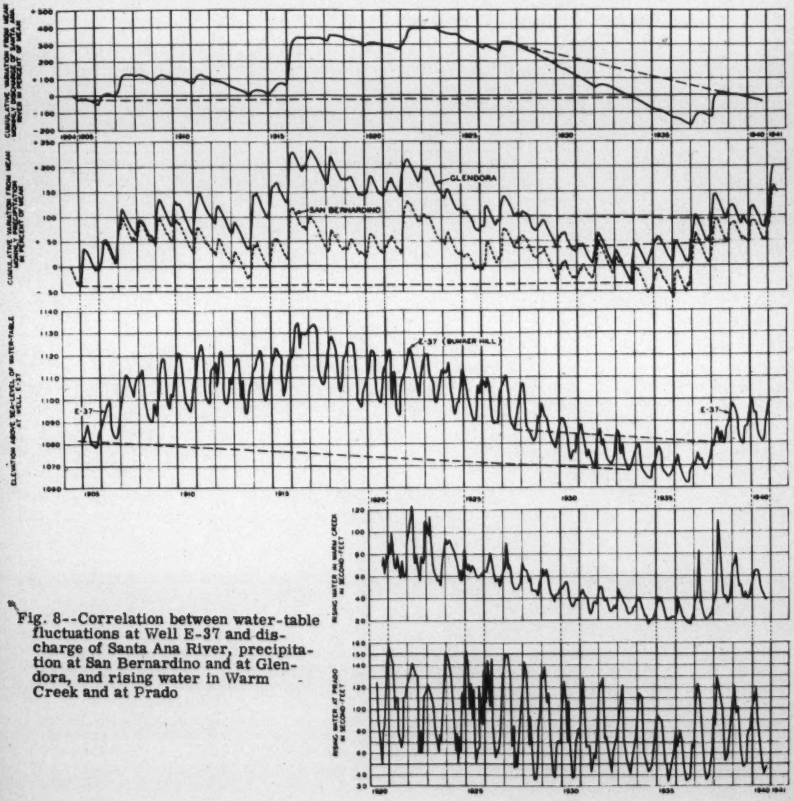


Fig. 8--Correlation between water-table fluctuations at Well E-37 and discharge of Santa Ana River, precipitation at San Bernardino and at Glendora, and rising water in Warm Creek and at Prado

different than at Glendora, the principal difference being less variation between long wet and dry periods. In earlier studies by the Division of Water Resources it has been found that the regimen of precipitation at San Bernardino has been very much like that in San Fernando Valley, while that over all the rest of the South Coastal Basin, including the mountains above San Bernardino has closely followed that at Glendora.

The correlation between cumulative variation from mean rainfall and water-table fluctuations at Well E-37 is not so pronounced as that shown for San Gabriel Valley. It is probable that spreading operations along Santa Ana River and numerous smaller streams draining into the area have had considerable effect. The well lies close to the pressure-zone and rising-water area above Bunker Hill Fault. Unfortunately, the only other long-record well, E-109, the graph of which is shown on a later Figure is also located in an area of high water-table. In such an area, the proximity of the ground-surface, with the resulting drainage, and the relatively constant underflow from higher areas, limit the range of fluctuation.

During the 11-year period, 1927-28 to 1937-38, the inflow from Santa Ana River was less than the long-time mean as was shown to be true in the case of the San Gabriel, while precipitation at San Bernardino was slightly greater than the mean. The period, however, is still useful as a base from which to estimate occurrences during a longer period or under different conditions.

Rising water in Warm Creek, brought to the surface by Bunker Hill Dike, increases in amount as Well C-37 rises and decreases as it falls. The abnormal variations in some of the earlier years shown and in 1937 and 1938 are probably in part due to the inclusion of some storm-water in the measurements.

The wide variations in the measurements at Prado are probably in part due to the same thing, but the actual variation in rising water from month to month is probably largely due to the long reach of dense vegetation lying along the river above the point of measurement.

Chino, Cucamonga, Pomona, and Rialto basins--Figure 9 shows fluctuations at wells in Chino, Cucamonga, Pomona, and Rialto basins, the last three tributary to the first. The boundaries of all of these are well defined. In the smaller basins there is considerable clay and the materials are quite irregular. Throughout most of Chino Basin the materials are open and water moves from point to point with ease. In the southerly portion there is a semi-artesian zone and immediately north of the Santa Ana River there is pronounced resistance to underflow, resulting in a steeply sloping water-table there. The mountain watershed tributary to Chino Basin is extremely small. As compared with the size of the basins themselves, the area tributary to Cucamonga and Rialto basins is relatively large. Little mountain water reaches Pomona Basin directly.

Well-records in all of these basins are somewhat fragmentary, but there is an indication that all probably dropped a little during the 29-year period and in all but Rialto Basin there was a drop during the 11-year period. Only in Pomona Basin was this drop large, however, and it may be that elsewhere, had the 11-year average inflow from the mountains been as great as the long-time mean, the water-table would not have dropped. In any event the overdraft, if one exists, is small in Cucamonga Basin. In Pomona Basin, where mountain inflow is negligible, it is no doubt larger and because of its large area and small mountain inflow even the small drop in Chino Basin probably indicates an overdraft. In Rialto Basin, spreading operations and extractions are such that variations from place to place are large. While Well D-1072 shows a rise during the 11-year period, records at other points indicate that there was a small drop over the basin as a whole. With the relatively large mountain inflow, however, it is not likely that this small drop indicates an overdraft.

Yucaipa, Devil Canyon, Bunker Hill, Riverside, and Temescal basins--Figure 10 shows water-table fluctuations in Beaumont, Yucaipa, Devil Canyon, Bunker Hill, Riverside, and Temescal basins. The boundaries of Devil Canyon, Riverside, and Temescal basins are quite well defined, as are all but the south boundary of Bunker Hill Basin. Ground-water may cross this boundary as well as a considerable portion of the boundaries of Beaumont and Yucaipa basins with relative ease. The north boundary of Temescal Basin is the Santa Ana River and ground-water here enters the river as rising water.

In Beaumont and Yucaipa basins the recent alluvium on the surface is underlain with Older alluvium and folded Fernando formation. This latter, although water-bearing, is quite dense and irregular and wells within short distances vary widely in water-table elevation. In Riverside and Temescal basins the material is mostly Older alluvium except along stream-channels where it is more recent. Movement is slower there than in either Devil Canyon or Bunker Hill basins. In the

latter the material is loose and water moves freely from place to place. The scale used on Figure 10 again does not show true elevation as between wells.

Only in Beaumont and Yucaipa basins has the drop been great enough during the 11-year period to indicate a significant overdraft. While the wells shown are not necessarily key wells for the basins as a whole, a study of all available records shows that there has been a general drop in the water-table.

In Bunker Hill Basin the drop during both the 29- and 11-year periods at wells E-37 and E-109 has been small. It appears probable that had the average annual inflow from the mountains,

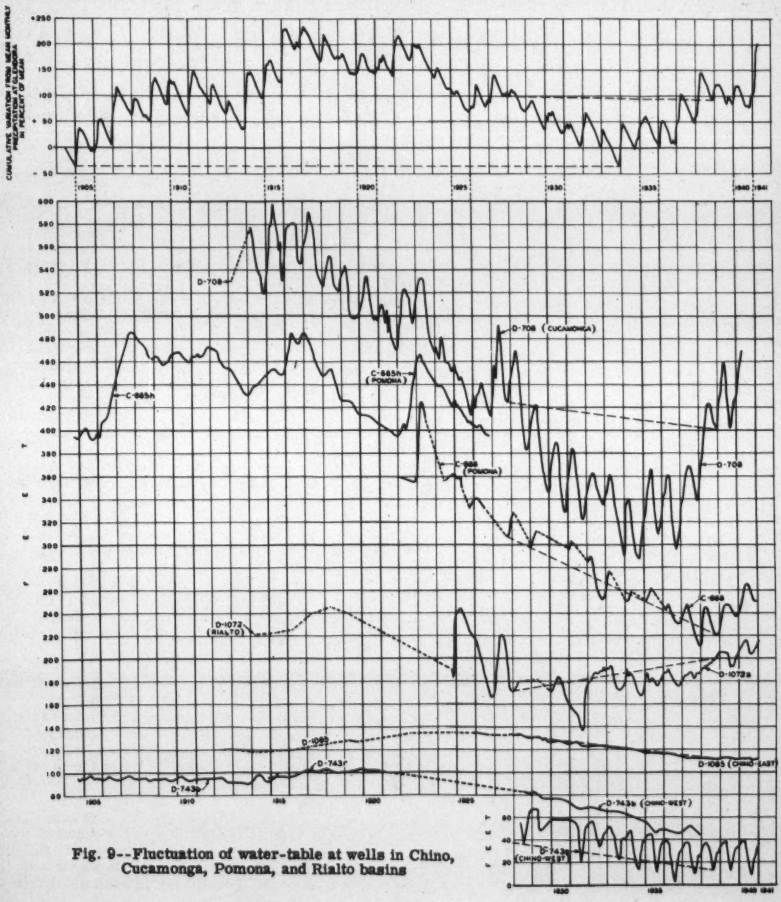


Fig. 9--Fluctuation of water-table at wells in Chino, Cucamonga, Pomona, and Rialto basins

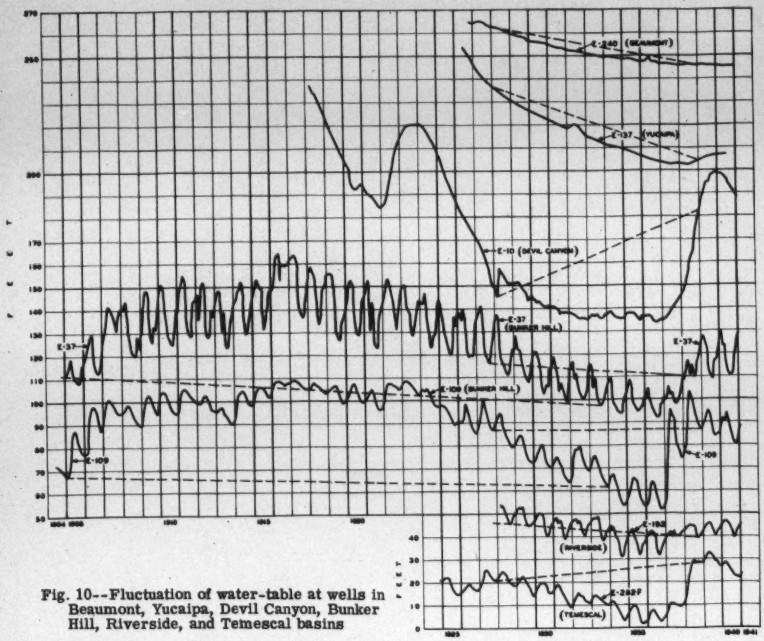


Fig. 10--Fluctuation of water-table at wells in Beaumont, Yucaipa, Devil Canyon, Bunker Hill, Riverside, and Temescal basins

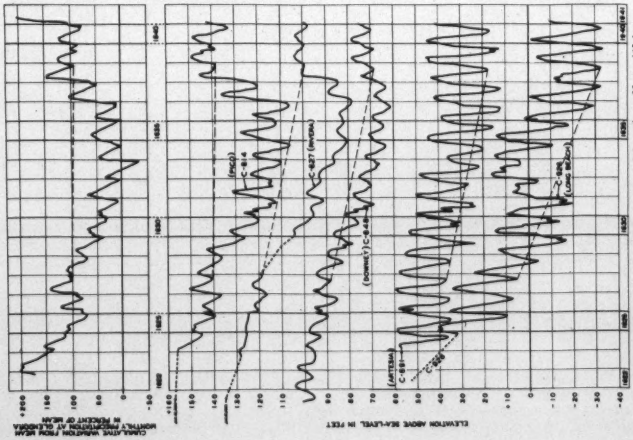


Fig. 11--Fluctuation of water-table at wells within San Gabriel River influence on Coastal Plain

an important part of the water-supply here, been equal to the long-time mean during the 11-year period, the water-table would not have dropped. The same is true in Riverside Basin. While the water-table rose at Well E-282f during the 11-year period, it dropped at other points in Temescal Basin so it is believed that there was neither a rise nor a fall over the basin as a whole.

Coastal Plain--On Figure 11, wells on the Coastal Plain within the probable influence of San Gabriel River are shown. The Coastal Plain lies between the intermediate range of hills and the Inglewood Fault-Zone. While some ground-water no doubt passes it, the fault-zone is a distinct barrier to its movement.

Water from the basins above enters the Coastal Plain through openings cut through the intermediate range by the three rivers at Los Angeles Narrows, Whittier Narrows, and Santa Ana Canyon. For only a short distance below the upper boundary is there much percolation to the ground-water, while the points at which percolation, other than that in the main stream-channels, virtually ceases are not sharply defined. The dotted line shown on Figure 1 marks the approximate boundary below which ground-water strata are overlain with more or less continuous beds of clay. In all of this zone there is little percolation. Since the water-bearing strata there are full at all times, changes in the elevation of ground-water at the wells indicate changes in pressure only and do not represent changes in storage. All change in storage on the Coastal Plain occurs in the forebay areas upstream from the pressure-zone.

Well C-814, near Pico, is quite close to Whittier Narrows and it is probable that the fluctuations at that point are influenced by variations in inflow through the Narrows. The water-table at this well dropped very little during the 11-year period. Farther downstream at wells C-827 near Rivera, and C-848 near Downey, the drop was greater. The latter well is quite close to the boundary of the pressure-zone as delimited by the dotted line and the uniform fluctuations indicating regulated inflow suggest that percolation is impeded there. Wells C-891 near Artesia and C-926 near Long Beach show the wide fluctuations characteristic of pressure-conditions.

The fact that the water-table at Well C-926 has dropped more rapidly than that farther north would indicate that the drawdown in this heavily pumped area is due in large part to the limited capacity of the aquifers in the pressure-zone rather than to the overdraft in the forebay-area.

A more detailed study indicates the drop during the 11-year period at wells C-827 and C-848 does represent some overdraft with supply and net extractions as they were during that period. In the final evaluation of this overdraft, the fact that operations above Whittier Narrows which indirectly control the amount of rising water, have a significant effect on fluctuations of the water-table below the Narrows, must be considered.

On Figure 12, water-table changes at wells C-1222 in the Irvine Forebay-Area, Well C-1129j near Anaheim in the Santa Ana Forebay-Area, and Well C-926 near Long Beach are shown.

At Well C-1129, the water-table dropped during the 11-year period at a slightly greater rate than during the 29-year period. The drop during the 11-year period was about equal throughout the area from Irvine to Long Beach, although annual fluctuations were quite different in each of the forebay-areas and the pressure area of the Coastal Plain. The uniformity of drop is significant in that it indicates that an appreciable change in the direction of underflow in various portions of the Coastal Plain is unlikely.

San Fernando Valley and West Coast--Figure 13, water-table fluctuations at two wells in San Fernando Valley (A-15 and A-40), and at two on the West Coast (B-10p and B-136) are shown.

San Fernando Valley is surrounded by mountains and hills, all outflow both surface and underground, leaving the valley at Los Angeles Narrows. The material in the westerly half of the basin is relatively dense. In the easterly portion it is loose and ground-water moves easily.

The water-supply to the westerly portion comes from relatively small runoff from surrounding low mountains and hills, from some deep percolation from aqueduct-water applied for irrigation, and in a large part from precipitation directly on the area. In the easterly portion the mountain inflow in Pacoima and Tujunga creeks is larger, and aqueduct-water is spread in considerable amount.

The West Coast Basin lies between Inglewood Fault and the Pacific Ocean. So far as is known there is no barrier to ground-water movement at the shore-line. Outside the pressure-zone which lies in the synclinal area just southwest from the fault, the material is sandy and water should

move easily from place to place. Aside from the comparatively small percolation from streams draining Santa Monica Mountains on the northwest, and small underflow through Inglewood Fault, the principal supply to this area is from rainfall on the surface.

At Well A-15 in the westerly part of San Fernando Valley, the water-table remained about level during the 11-year period of long-time mean precipitation. At A-40, in easterly portion, there was a considerable rise. This is doubtless due to the influence of water spread from Pacoima and Tujunga creeks and the Los Angeles Aqueduct.

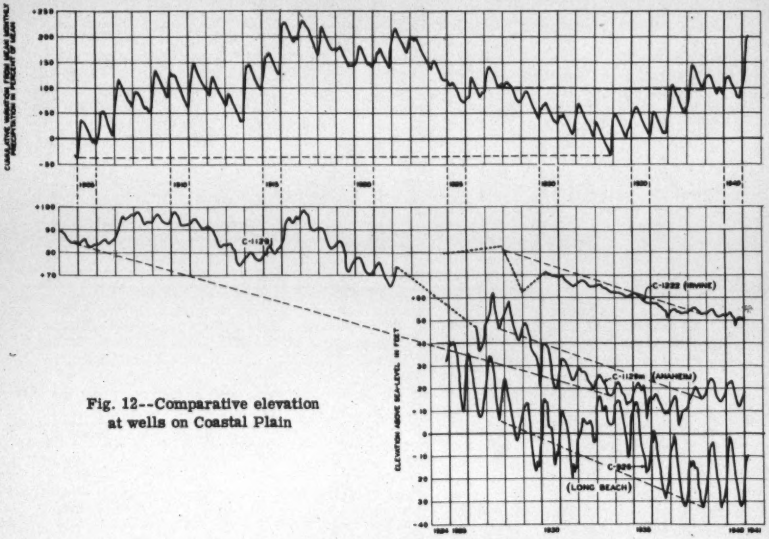


Fig. 12--Comparative elevation at wells on Coastal Plain

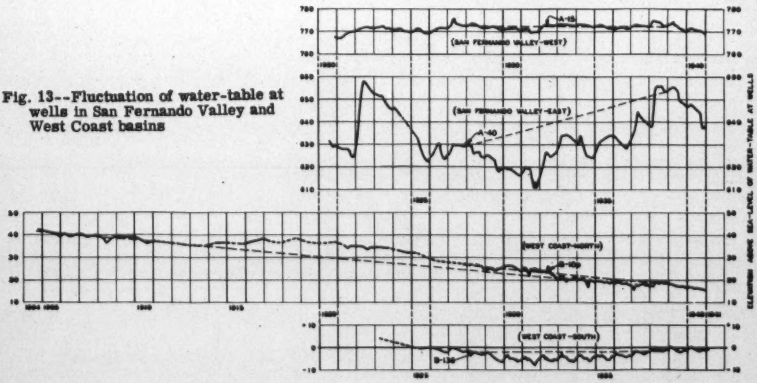


Fig. 13--Fluctuation of water-table at wells in San Fernando Valley and West Coast basins

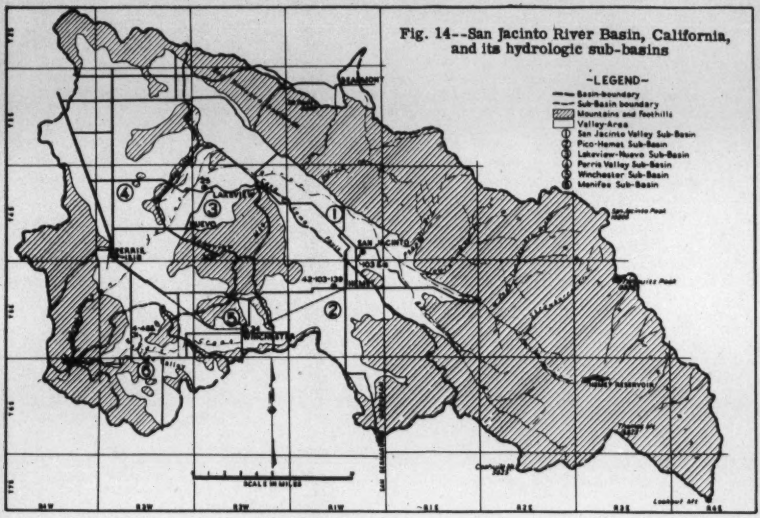


Fig. 14--San Jacinto River Basin, California, and its hydrologic sub-basins

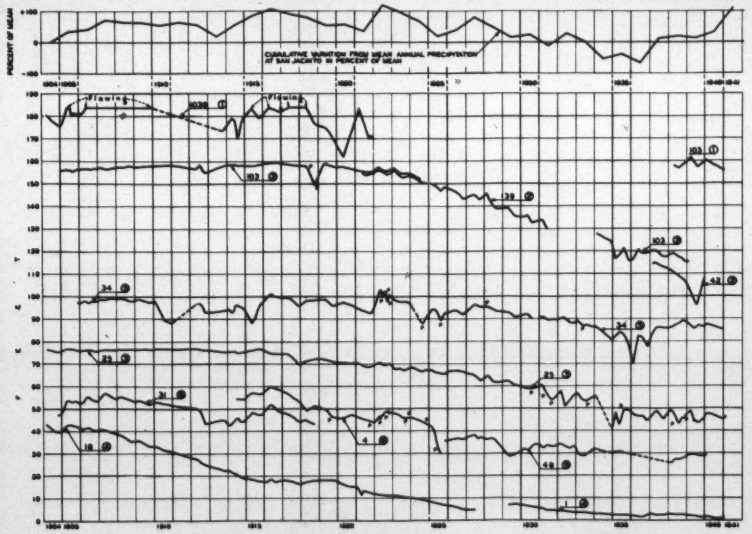


Fig. 15--Fluctuation of water-table at wells in San Jacinto River Valley

In the northerly portion of West Coast Basin at Well B-10p, a comparatively small but continuous drop occurred throughout the 29-year period and has continued to date. This no doubt represents an overdraft. In the south portion at Well B-136, the water-table is below sea-level and no drop occurred during the 11-year period.

An interesting feature, both at the West Coast wells and in the westerly portion of the San Fernando Valley, is the small amount of fluctuation from month to month.

San Jacinto River Basin--San Jacinto River Basin lies outside the area defined as South Coastal Basin. It adjoins it on the east, however, and is tributary to Lake Elsinore which after a series of wet years might discharge into Temescal Creek and thus add to the flow in Santa Ana River.

Limitations as to space make it impossible to discuss this area in detail, but the map on Figure 14 and the graphs on Figure 15 show the extent of the area, the location and boundaries of the six ground-water basins included, and a graphical presentation of records at one well in each. The purpose of the presentation is to show what has happened in this area as compared with occurrences in South Coastal Basin.

In any of the ground-water basins in both areas, it is probable that a large drop in water-table elevation during a period of approximately normal supply is indicative of an overdraft. In the final evaluation of the overdraft, however, the fact that the historical drop represents overdraft for only the average conditions which existed during the historic period should be considered. Changes in any of the governing conditions, brought about either artificially or naturally, might result in either an increased drop or no drop at all in a later period of normal supply.

State of California,
Department of Public Works,
Division of Water Resources,
Los Angeles, California

RUNOFF IN THE SANTA YNEZ RIVER BASIN, CALIFORNIA, FOLLOWING THE EXCESSIVE RAINFALL OF 1940-41

G. A. La Rocque, Jr.

(Published with the approval of the Director, Geological Survey, United States Department of the Interior)

Introduction--This paper reports briefly on the runoff-characteristics of the Santa Ynez River in Santa Barbara County, California, following the excessive rainfall in the winter of 1940-41; also, it contrasts these conditions of 1940-41 with earlier years of less rainfall. The data for this report were compiled in connection with an investigation of the water-resources of Santa Barbara County which is being conducted by the United States Geological Survey in cooperation with the County of Santa Barbara.

The Water Resources Branch of the Geological Survey and the Water Department of the City of Santa Barbara have maintained stream-gaging stations at four sites on the Santa Ynez River for periods ranging from 13 years to 22 years. During 1941, the Geological Survey established three additional stations on tributaries of the main stream. Many other miscellaneous measurements of stream-flow have been made elsewhere in the basin. The stream-flow data here presented for the period ending with 1939 have been taken from Water-Supply Papers of the Geological Survey. Those for 1940 and 1941 are tentative and have not been published; in advance of publication, they have been made available by the suboffice of the Geological Survey at Los Angeles. These data for 1940 and 1941 are subject to revision but probably not to an extent that will materially influence the conclusions reached in this paper. The data on rainfall are taken mainly from publications of the United States Weather Bureau and from unpublished data compiled by the United States Engineer Department.

The writer gratefully acknowledges the assistance and constructive criticism of his associates in the Geological Survey who have aided materially in the preparation of this paper.

General features of the Santa Ynez Basin--The Santa Ynez River is about 85 miles long and drains an area of about 900 square miles, which lies almost wholly within Santa Barbara County (see Fig. 1). It heads in the mountains along the boundary between Santa Barbara and Ventura

counties and flows nearly due west to the Pacific Ocean near Surf, about seven miles north of Point Arguello. Its basin is flanked on the south by the Santa Ynez Range.

The Santa Ynez Basin, like much of the Pacific Slope in the United States, has heavy rainfall in winter but little or none in summer. This rainfall is very unevenly distributed. At Surf, which is at the western end of the valley on a low coast, the yearly rainfall is only about ten inches; in the mountainous headwater-area, on the other hand, the yearly precipitation is about 35 inches, in part as snow. In general, the rainy season ends by early April; thereafter the flow in the Santa Ynez River declines to a minimum in mid-August.

The Santa Ynez Basin may be divided into four sub-areas or reaches, each distinct in hydrologic and geologic features, as follows: (1) The mountainous headwater-area upstream from San Lucas Bridge includes an area of about 435 square miles, most of which is underlain by folded, consolidated sedimentary rocks. Unconsolidated materials occur only as isolated small bodies of alluvium in local bedrock-basins along the stream. This terrane has relatively little infiltration-capacity so that rainfall is detained only briefly; nearly all runs off immediately. (2) From San Lucas Bridge downstream to and a few miles beyond Buellton the river is flanked on the south by

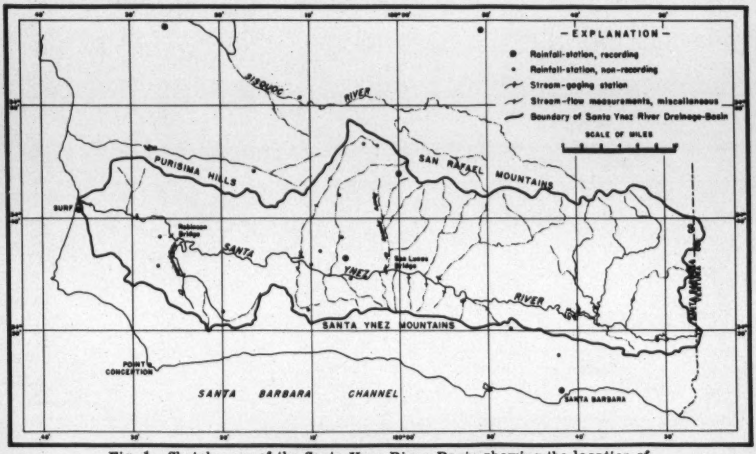


Fig. 1--Sketch-map of the Santa Ynez River Basin showing the location of rainfall and stream-gaging stations

the Santa Ynez Range but to the north by a terraced terrane which is about 200 square miles in extent and which is underlain by semi-consolidated deposits of alluvial origin. These semi-consolidated materials probably have a considerable aggregate capacity to hold water in storage. Such data as are available suggest that an appreciable part of the water so stored during the winter subsequently is discharged gradually into the river. (3) The next reach in downstream order is about 18 miles long and extends to Robinson Bridge near Lompoc. Here the river flows in a narrow channel, almost entirely on impervious bedrock; only narrow strips of pervious alluvium lie along the river on either side. Thus, only a small or moderate fraction of the rainfall is detained as ground-water storage; very little ground-water is discharged into the river except possibly from the valley of Salsipuedes Creek. (4) In the downstream reach, which extends from Robinson Bridge to the sea, the river traverses the so-called Lompoc Plain. This plain extends over about 100 square miles and is underlain by unconsolidated deposits of considerable thickness. Here a considerable quantity of water appears to infiltrate from the river to this body of unconsolidated material and is detained as ground-water storage.

Rainfall and runoff in the Santa Ynez River Basin--Figure 2 shows the yearly rainfall at five principal stations in Santa Barbara County. From 1919 through 1940 rainfall was markedly

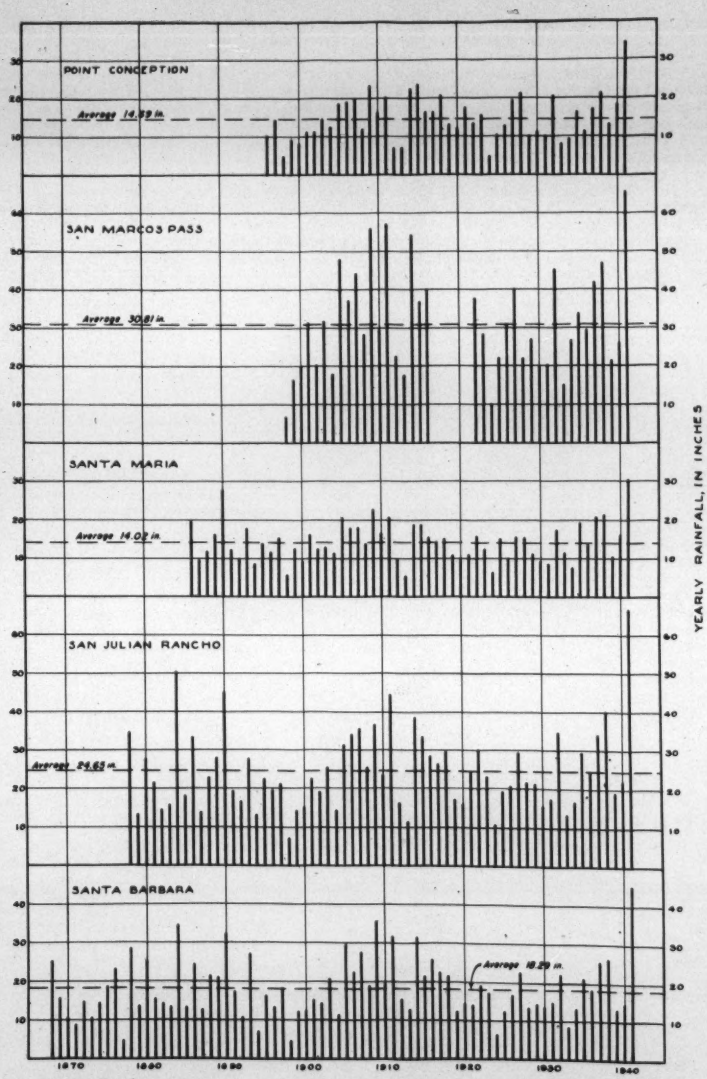


Fig. 2--Yearly rainfall at five stations in Santa Barbara County, California, 1868-1941

deficient in Santa Barbara County, especially through 1934. During these 16 years the accumulated deficiency ranged from about 210 per cent to about 320 per cent of the long-term yearly average. During the 12 years from 1929 through 1940, for which stream-flow records are available, the accumulated deficiency was less, in part because rainfall was greater than average in 1937 and 1938. In that 12-year period the accumulated rainfall ranged from a slight excess at the San Julian Rancho in the Salsipuedes Valley to a deficiency of about 105 per cent at Santa Barbara.

In contrast, rainfall for the year ending June 30, 1941, was greater than for any year previously recorded. At the stations where rainfall has been measured for more than 40 years, the yearly rainfall for 1940-41 ranged from about 205 per cent to about 245 per cent of the long-term average. This excessive rainfall was accompanied by exceptionally large aggregate runoff from the Santa Ynez River Basin as shown in Table 1. Although the runoff was great, neither a new extreme flood-height nor a new extreme flood-discharge was established by the Santa Ynez River, probably because the storms were widely spaced in time and of moderately low intensity.

Table 1--Monthly runoff of the Santa Ynez River Basin at three gaging-stations in thousands of acre-feet

Month	Below Gibraltar Dam	At San Lucas Bridge	At Robinson Bridge
1940-41			
December	1.13	4.38	8.26
January	11.1	25.9	59.4
February	34.2	98.7	135.0
March	73.2	190.5	250.7
April	46.7	121.0	145.3
May	11.1	22.4	31.5
June	3.92	7.24	11.5
July	1.28	3.18	5.57
August	0.32	1.26	2.48
September	0.11	0.57	1.71

For the year ending September 30, 1941, the flow of the river at San Lucas Bridge was 475,100 acre-feet or 820 per cent of the average for the 12 years preceding; at Robinson Bridge the flow was 651,400 acre-feet or 855 per cent of the 12-year average. The increase in flow between San Lucas Bridge and Robinson Bridge was 176,300 acre-feet or 960 per cent of the 12-year average. Table 2 shows the monthly flow at these two gaging-stations and the increase in flow between them, all in terms of the respective 12-year monthly averages.

Table 2--Monthly discharge at two gaging-stations on the Santa Ynez River from December, 1940, through September, 1941, expressed in terms of the average for the twelve years preceding

Month	Ratio $\left(\frac{\text{Discharge during 1941}}{\text{Average discharge 1929-40}}\right)$		
	At San Lucas Bridge	Increase in flow, San Lucas Bridge to Robinson Bridge	At Robinson Bridge
1940-41			
December	4.56	4.92	4.72
January	7.78	12.37	9.84
February	5.52	3.69	4.87
March	8.09	9.76	8.44
April	22.05	10.90	18.83
May	14.64	11.79	13.68
June	15.77	27.38	18.72
July	28.12	54.20	34.99
August	42.00	86.52	56.24
September	41.53	58.21	51.35

From May through September 1941 the flow was 1,610 per cent of the 12-year average at San Lucas Bridge and 1,670 per cent at Robinson Bridge; the increase in flow between San Lucas Bridge and Robinson Bridge was 1,800 per cent of the 12-year average. In August 1941 the

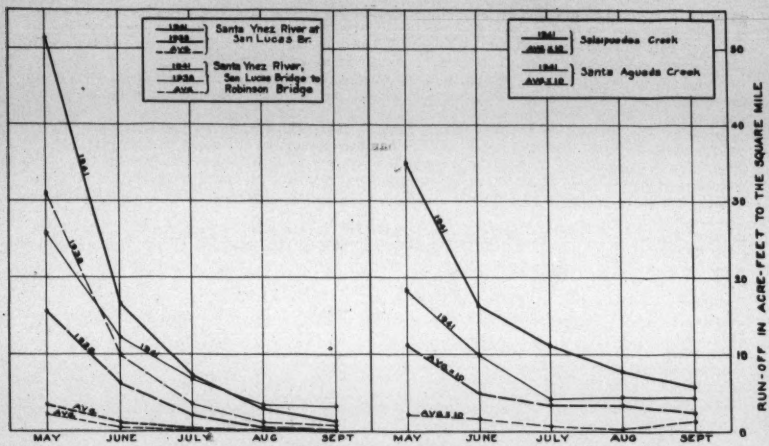


Fig. 3--Comparison of summer flow from areas of consolidated rocks and unconsolidated deposits

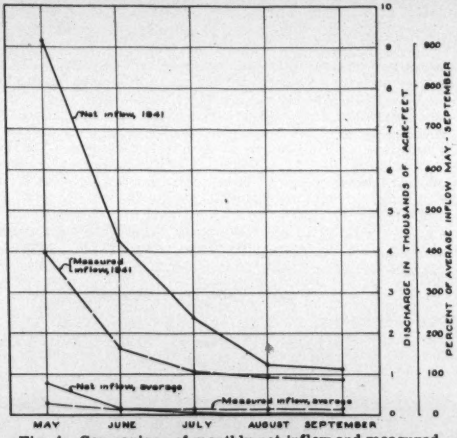


Fig. 4--Comparison of monthly net inflow and measured inflow below San Lucas Bridge

percentage-flows were greatest--4,200 per cent, 8,200 per cent, and 5,620 per cent, respectively.

The drainage-areas above San Lucas Bridge and between that place and Robinson Bridge are nearly equal in extent--about 400 and 355 square miles, respectively. During the 12-year period ending with 1940 the runoff from these two areas was about 5.5 acre-feet and 3 acre-feet per square mile per inch of rainfall, respectively. This period includes the greatest flood of record, in 1938. During 1941 the water-productivity of the respective areas was roughly four times as great--about 20 acre-feet and 13 acre-feet per square mile per inch of rainfall (by estimate, in

part). The difference in water-productivity of the two areas is probably due in large part to greater percentage-infiltration of rainfall in the semi-consolidated alluvial deposits that lie north of the river between San Lucas Bridge and the vicinity of Buellton.

The left-hand graph of Figure 3 shows the monthly runoff during the summer from the area above San Lucas Bridge, which is formed largely of consolidated rocks, also from the area next downstream ("net inflow"), in which unconsolidated deposits are relatively extensive. This graph includes curves for: (1) 1938, the year of greatest recorded flood and of second largest total runoff; (2) 1941, the year of greatest total runoff; and (3) the average for the 12 years ending with 1940. The right-hand graph of Figure 3 shows the corresponding summer runoff in 1941 from two tributary streams, Santa Agueda and Salsipuedes creeks. Like the larger area above San Lucas Bridge, the basin of Salsipuedes Creek is composed largely of consolidated sedimentary rocks. The basin of Santa Agueda Creek is a part of the area between San Lucas Bridge and Robinson Bridge; it is formed largely of semi-consolidated alluvial deposits. All the curves of Figure 3 show that the rate of decline in runoff from the areas of unconsolidated deposits is slower than from the areas of consolidated rocks.

During the 12-year period ending with 1940 the diminution in runoff from the area above San Lucas Bridge each month of the summer was on the average 69 per cent of the runoff in the preceding month. In 1941 the average monthly diminution in summer flow was 64 per cent. The corresponding rates of diminution for the area below San Lucas Bridge are 49 per cent for the 12-year period and 43 per cent for 1941. Thus, in both areas the depletion of runoff in the summer following the excessive rainfall of 1941 was slower than the average of the preceding 12 years and slower than in 1938.

These differences in rates of depletion of runoff from the areas above and below San Lucas Bridge during the summer are believed due to detention of a larger percentage of the rainfall and runoff in the ground-water reservoirs below San Lucas Bridge. Supporting evidence is presented in Figure 4, which shows monthly "net inflow" and "measured inflow" for the downstream area. "Net inflow" is the flow of the river at Robinson Bridge minus the flow at San Lucas Bridge. "Measured inflow" is the summation of the flows from Santa Agueda, Santa Cota, Alamo Pintado, Nojoqui, and Salsipuedes creeks (see Fig. 1); together, these creeks drain the greater part of the downstream area. Thus, on the average in the 12-year period, there was a net loss of flow from July to September in the reach between San Lucas Bridge and Robinson Bridge due to evaporation, transpiration, surface-diversion, and possibly some infiltration to the water-table. In contrast, there was a net gain in flow during 1941, probably due largely to movement of stored ground-water into the river.

U. S. Geological Survey,
Santa Barbara, California

CHANGE IN GROUND-WATER ELEVATION IN VARIOUS PUMPING-AREAS, VENTURA COUNTY, CALIFORNIA, 1928 TO 1942

Richard H. Jamison

Introduction--Ventura County is an area in which intensive agriculture of high type has been developed under irrigation. Practically all of the water for domestic, irrigation, and industrial use is secured by pumping from the underground supply.

The purpose of this report is to show, by means of graphs, the change in ground-water elevation in the various pumping-areas, during the past 14 years.

Figure 1 shows the locations of these pumping-areas, their relation to one another and to their contributing watersheds. On the following Figures more details are shown, such as location of wells and the location of the underground sections. The dates selected to show the change in ground-water elevation are as follows: January, 1928, because it is near the beginning of most of the records of depth to water; January, 1932, because it was the lowest elevation in some of the areas and also the beginning of the period when the rate of recession decreased in those areas where there was no recovery; May, 1941, because it was the date of highest elevation in some of the areas; and January, 1942, the end of the records.

Rainfall--A record of rainfall showing the yearly amount in inches, the yearly per cent of the 50-year annual mean, and the cumulative variation from the 50-year annual mean by means of

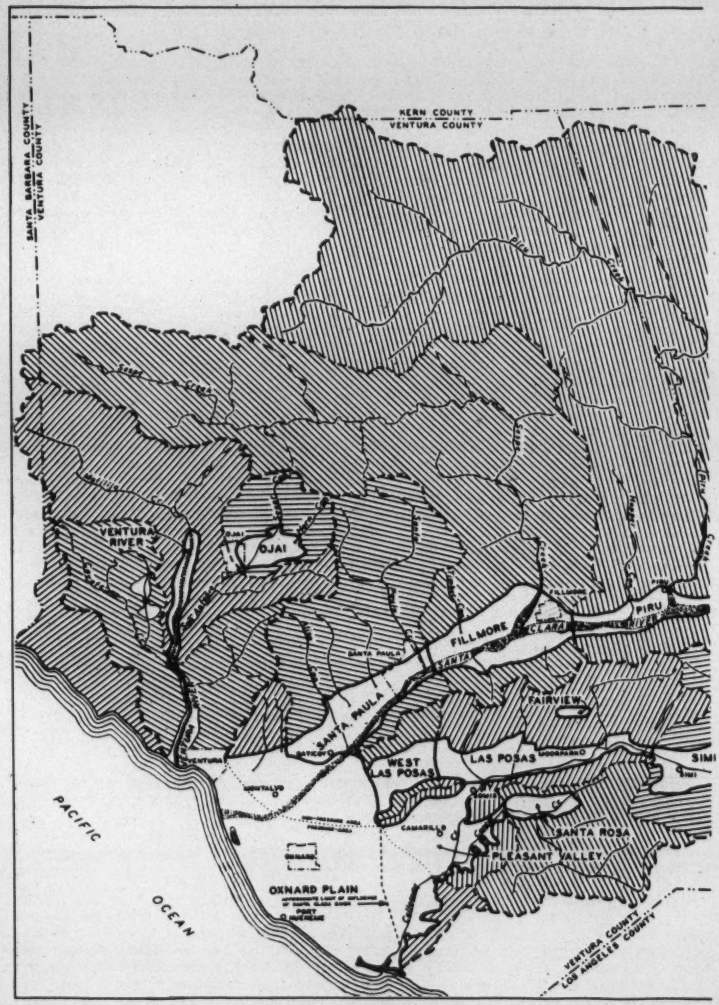
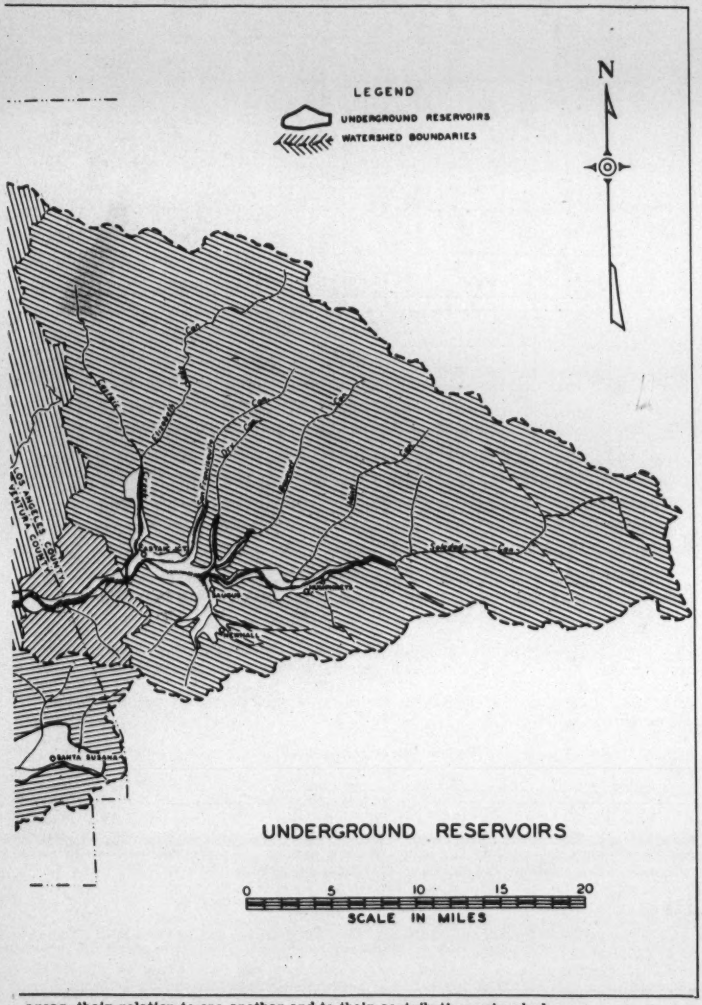


Fig. 1--Ventura County, California, Water-Survey: Locations of pumping-



areas, their relation to one another and to their contributing watersheds

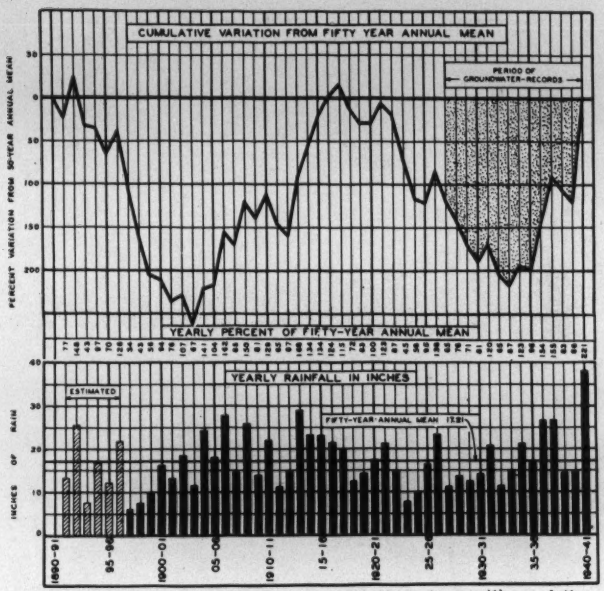


Fig. 2--Record of rainfall at Santa Paula, 1891-1941, showing (1) cumulative variation from 50-year annual mean, (2) yearly per cent of 50-year annual mean, and (3) yearly rainfall in inches

a graph are presented in Figure 2. This is a record of rainfall at Santa Paula. It is included to show the per cent of the annual mean for each year of the 14-year period covered by the groundwater data and the relation of this 14-year period to the 50-year period. The record does not represent the amount of rain received in the various areas but it does show the order in which the rain occurred in all areas.

Ventura River Drainage-Basin

Ojai Valley, Figure 3--Ojai Valley Basin occupies a depression in the Ventura River Watershed. The ground-surface of the valley is rather steep and its drainage is through San Antonio Creek to the Ventura River. The basin is small and the water-table rises rapidly with high rainfall and runoff. Figure 3 shows the change in ground-water elevation during the period 1928-41. The highest elevation of the water-table recorded was in May, 1941. The water-table does not remain long at this elevation because of the rapid natural drainage from the basin.

Ventura River Valley, Figure 4--The Ventura River Basin as used here is that portion of the valley lying above the mouth of Coyote Creek. It is about six miles long and three-quarters of a mile wide. The valley-fill is not deep; bedrock is encountered at from 40 to 80 feet. There are not many wells in the area and it is not feasible to show a profile as in the Ojai Valley. Figure 4 shows the hydrographs at three wells, one near the north end, one near the center, and one near the south end of the valley. There has been a slight trend upward since the low point in 1931.

Santa Clara River Drainage-Basin

Eastern Basin, Figure 5--The name Eastern Basin is used to designate that portion of the Santa Clara River lying east of the mouth of Castaic Creek. It is made up of a number of small

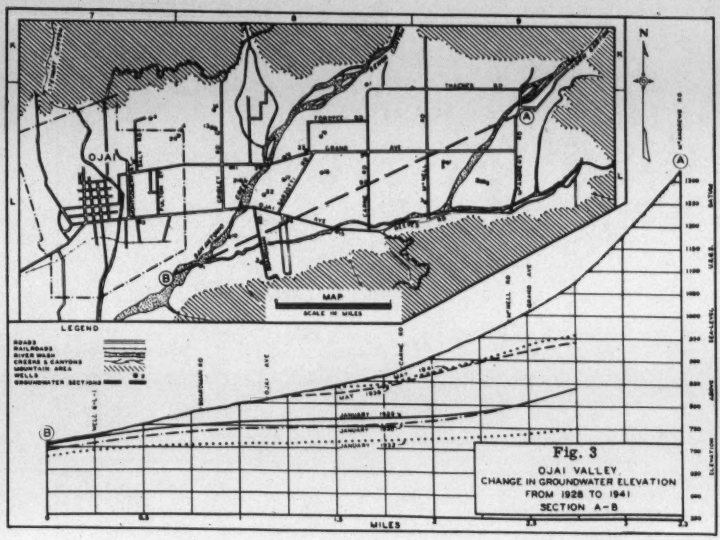


Fig. 3
OJAI VALLEY
CHANGE IN GROUNDWATER ELEVATION
FROM 1928 TO 1941
SECTION A-B

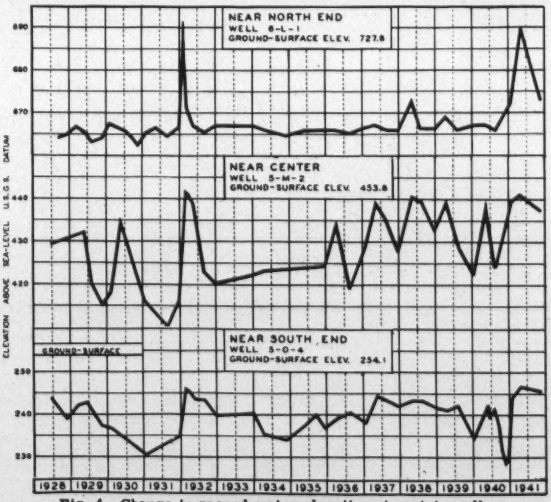


Fig. 4--Change in ground-water elevation at certain wells, Ventura River, 1928-41

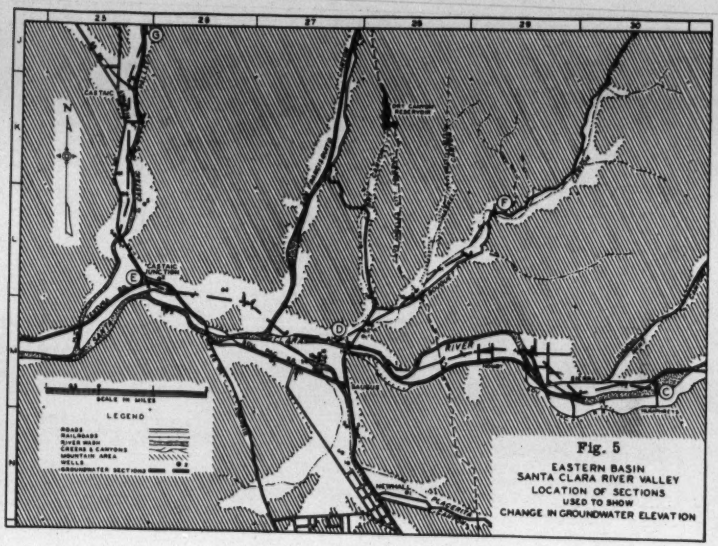


Fig. 5
EASTERN BASIN
SANTA CLARA RIVER VALLEY
LOCATION OF SECTIONS
USED TO SHOW
CHANGE IN GROUNDWATER ELEVATION

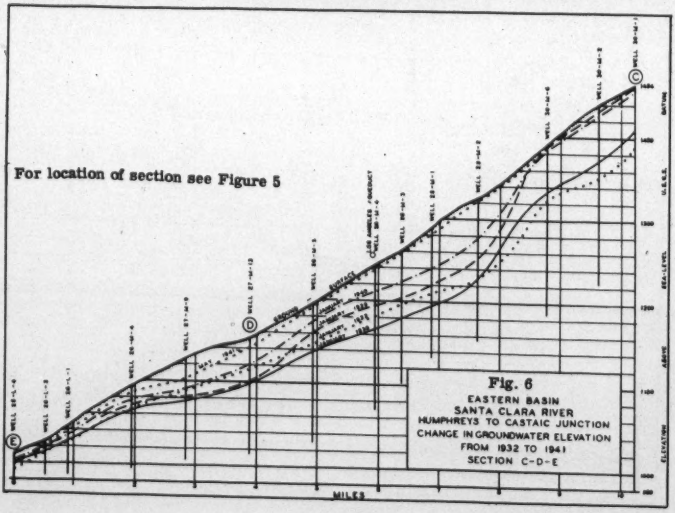


Fig. 6
EASTERN BASIN
SANTA CLARA RIVER
HUMPHREYS TO CASTAIC JUNCTION
CHANGE IN GROUNDWATER ELEVATION
FROM 1932 TO 1941
SECTION C-D-E

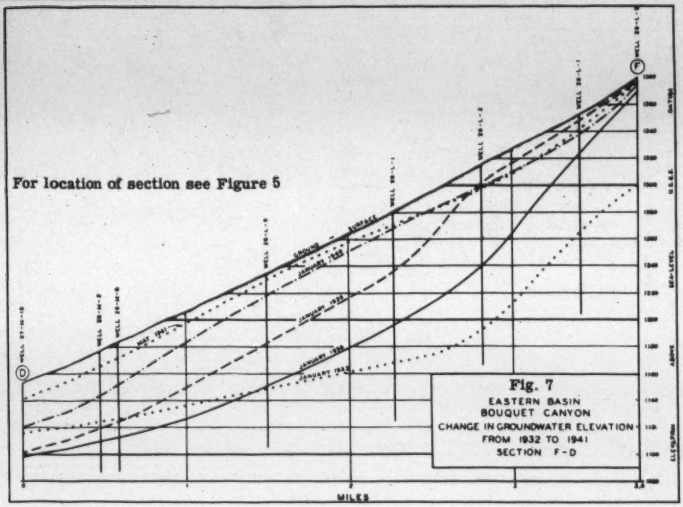


Fig. 7
EASTERN BASIN
BOUQUET CANYON
CHANGE IN GROUNDWATER ELEVATION
FROM 1932 TO 1941
SECTION F-D

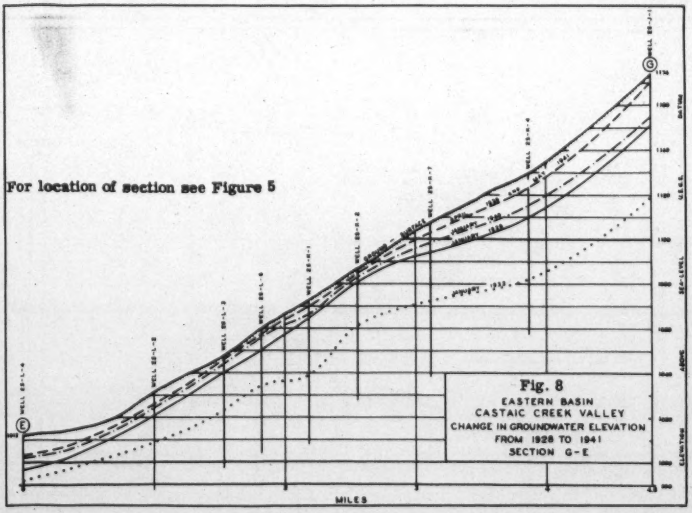


Fig. 8
EASTERN BASIN
CASTAIC CREEK VALLEY
CHANGE IN GROUNDWATER ELEVATION
FROM 1928 TO 1941
SECTION G-E

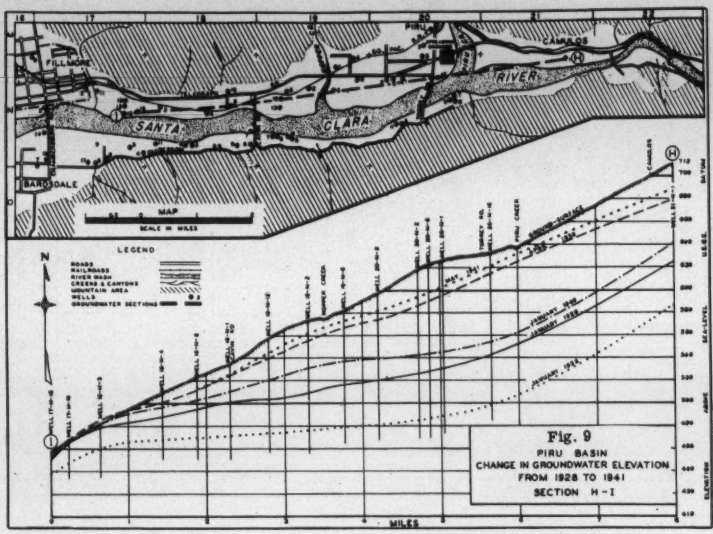


Fig. 9
PIRU BASIN
CHANGE IN GROUNDWATER ELEVATION
FROM 1928 TO 1941
SECTION H - I

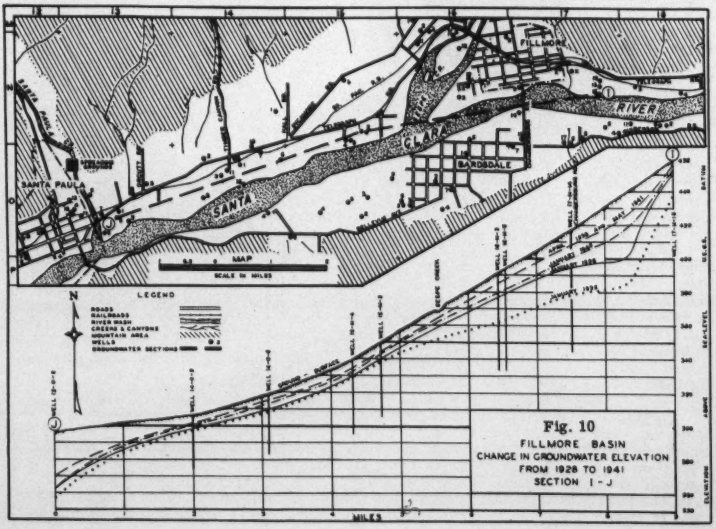


Fig. 10
FILLMORE BASIN
CHANGE IN GROUNDWATER ELEVATION
FROM 1928 TO 1941
SECTION I - J

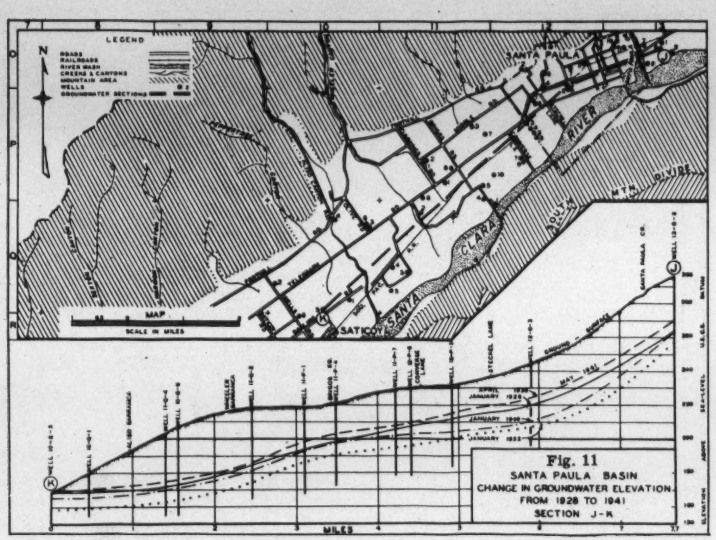


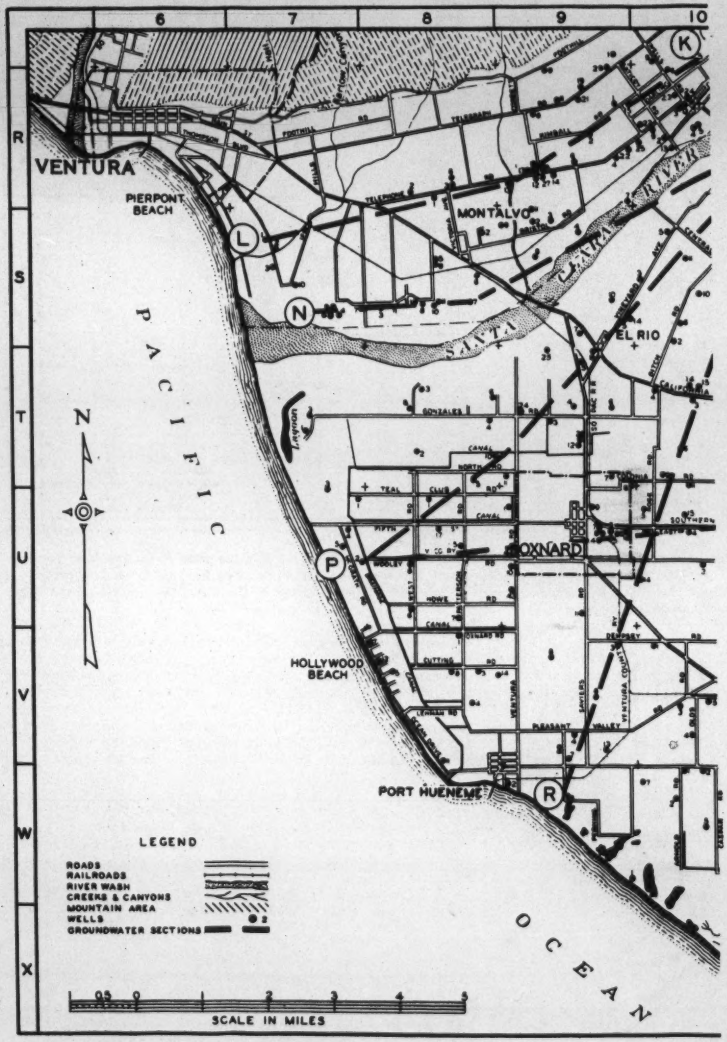
Fig. 11
SANTA PAULA BASIN
CHANGE IN GROUNDWATER ELEVATION
FROM 1928 TO 1941
SECTION J-K

underground reservoirs draining into Santa Clara River. All of the good wells are near the stream-channels. Three sections are presented to show the change in ground-water elevation, one along Santa Clara River, one of Bouquet Canyon and one of Castaic Creek. See Figure 5 for locations of the sections.

Santa Clara River, Figure 6--This section shows the change in ground-water elevation along the Santa Clara River between Humphreys and Castaic Junction. Pumping is light in the upper portion of the valley and there was some recovery here between 1932 and 1938. In the lower part of the valley where the pumping is heavy, the water-plane continued downward during the same period. The flood of March, 1938, filled the upper mile and one-half of the valley and there was a little recovery farther down the valley. Beginning in December, 1938, and ending April, 1939, the City of Los Angeles released 13,140 acre-feet of water from the aqueduct, near the middle of the section. Much of this water was retained in this basin below the aqueduct. The high point of the period was reached in May, 1941.

Bouquet Canyon, Figure 7--Bouquet Canyon drains into Santa Clara River (see point D on Figs. 5 and 6). The natural runoff is small, especially since the building of the Bouquet Canyon Dam by the City of Los Angeles. However, by agreement with the Santa Clara Water Conservation District, the City releases varying amounts of water each year. The amount to be released is determined by the amount of the rainfall. There was some recovery at the upper end of the valley during the period January, 1932, to January, 1938, but the water-plane continued downward in the lower part of the valley. Beginning in December, 1938, and ending April, 1939, the City released 3,380 acre-feet of water into this valley, and varying amounts since then. By May, 1941, the basin was practically full. Figure 7 shows the stages of recovery.

Castaic Creek, Figure 8--Castaic Creek is another tributary draining into Santa Clara River in the Eastern Basin (see point E on Fig. 5). During the period 1928-32, due to the low runoff and heavy pumping, the water-plane reached the lowest point of record. There was some recovery from January, 1932, to January, 1938, due to increased rainfall and runoff, and a reduction in pumping. The flood of March, 1938, filled the basin. The highest point was reached in April, 1938, and water flowed across the basin the remainder of the year. The position of the water-plane in January, 1940, indicates that the natural outflow from the basin was larger than the inflow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EL RIO
OXNARD
HOLLYWOOD BEACH
PORT HUENEME
PACIFIC
OCEAN
N
LEGEND
ROADS
RAILROADS
RIVER WASH
CREEKS & CANYONS
MOUNTAIN AREA
WELLS
GROUNDWATER SECTIONS
0.5 0 1 2 3 4 5
SCALE IN MILES

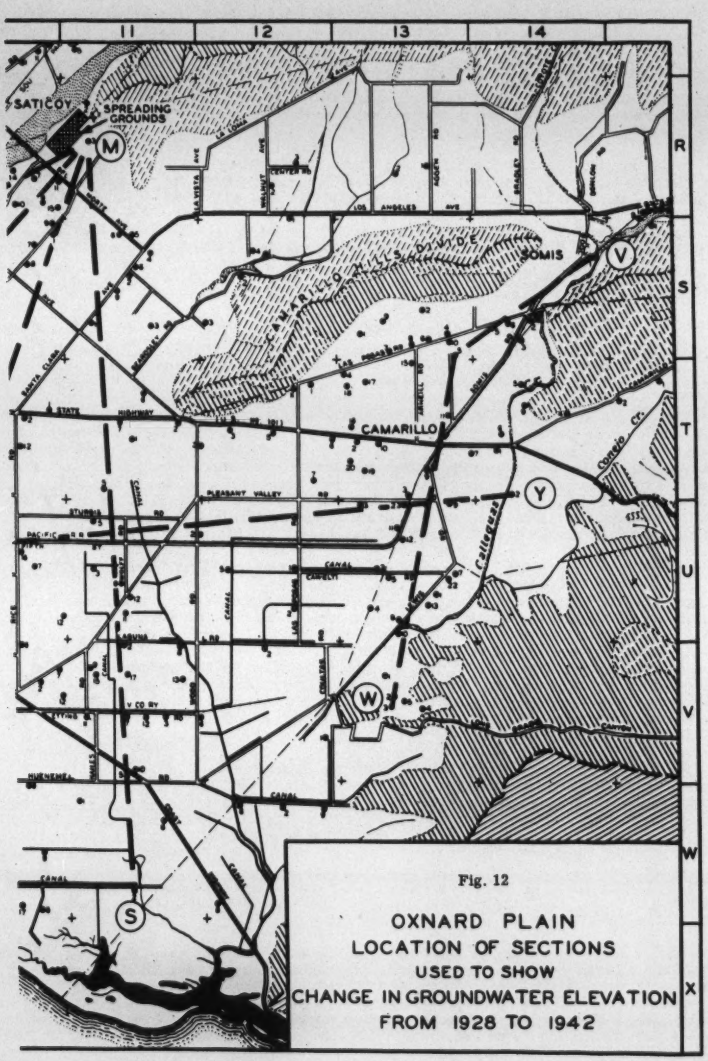

Fig. 12

OXNARD PLAIN
LOCATION OF SECTIONS
USED TO SHOW
CHANGE IN GROUNDWATER ELEVATION
FROM 1928 TO 1942

for the period April, 1938, to January, 1940, because the pumping during this period was small. The high rainfall and runoff during the season of 1940-41 again filled the basin.

Castaic Junction to Camulos--The ground-water from the Eastern Basin comes to the ground-surface in the vicinity of Castaic Junction, flows on the surface for a distance of about nine miles, and, if not diverted for use, sinks into Piru Basin in the vicinity of Camulos. There is no underground storage of any consequence in this nine-mile reach of the river. The bedrock is near or at the surface.

Piru Basin, Figure 9--All runoff from the Eastern Basin, Piru Creek, and Hopper Creek contributes to the Piru Basin. The ground-water elevation varies greatly. There was a general rise in the water-table after January, 1932, and a high point was reached in April, 1938. The amount of water that escapes from the lower end of the basin as surface-flow varies with the height of the water-plane. At the low point of record in January, 1932, there was no surface-outflow; at the April, 1938, elevation there was 44 cubic feet per second and at the January, 1940, elevation there was 18 cubic feet per second. Approximately 39,000 acre-feet escaped during the 21-month period. The highest point of record was reached in May, 1941. The surface-outflow was 57 second-feet in July, 1941, and on October 30, 1941, it was 53 second-feet.

In addition to the natural replenishment of the basin, the Santa Clara Water Conservation District operates spreading works located on Piru Creek cone (see Fig. 9). The annual report for 1940-41 of the District shows that a total of 54,333 acre-feet of water was conserved at the Piru spreading-grounds during the period 1928 to July, 1941.

Fillmore Basin, Figure 10--The principal sources of supply to Fillmore Basin are Sespe Creek and the runoff passing over and through Piru Basin lying to the east. The range of the water-plane fluctuation is not so great as that in Piru Basin. This is due to a larger available supply than that of Piru Basin and also because a large area in the vicinity of Bardsdale is irrigated by water conveyed to it by pumping from the lower end of Piru Basin. The elevation of the ground-water in May, 1941, was the same as in April, 1938. This was the highest elevation of the record. This is probably as high as the water-plane can ever attain because at this elevation the water-plane intersects the ground-surface near the mouth of Sespe Creek. The effluent water drains off rapidly.

Santa Paula Basin, Figure 11--The runoff of approximately 1,500 square miles passes through this basin. Usually the effluent water from Fillmore Basin and from Santa Paula Basin forms a live stream in the river through the entire length of the basin. However, during the summer of 1931, which was the period of lowest pumping level, the stream-bed became dry for a distance of about two miles near the center of the basins. Santa Paula Creek enters the basin from the north at Santa Paula. Any conservation underground of Santa Paula Creek water must take place on its debris-cone before reaching Santa Clara River. The Santa Clara Water Conservation District operates spreading-works on Santa Paula Creek cone near the mouth of the canyon (see Fig. 10 for location). The annual report for 1940-41 of the District shows that a total of 20,410 acre-feet of water was conserved at this location for the period 1928 to July, 1941. The range of the water-plane fluctuation is shown on Figure 11.

Saticoy-Montalvo Area, Figure 13--This is section K-L near the northern part of the map on Figure 12. The high water-plane to the right indicates the location of the barrier between the ground-water of the Santa Paula Basin and the ground-water to the west. It has been thought that the ground-water along the lower six miles of this section was not within the influence of the Santa Clara River. However, when a comparison is made with the profiles of the Oxnard Plain it will be seen that there is a marked similarity in the change in ground-water elevations.

Oxnard Plain, Figure 12--The term Oxnard Plain is used here to designate the broad coastal area shown on Figure 12. This map was prepared to show the locations of sections used to present the change in ground-water elevations in this area.

A part of Santa Clara River water, after passing the barrier which forms the western boundary of Santa Paula Basin, sinks naturally into the river-gravels to become later the underground water-supply of the Oxnard Plains. To augment this natural inflow to the underlying gravels, the Santa Clara Water Conservation District constructed spreading-works on the highest feasible area near the river. This is called the Saticoy Spreading-Works (see Fig. 12 for location). The report for 1940-41 of the District shows that a total of 138,650 acre-feet of water was spread at this location during the period 1928 to July, 1941.

Oxnard Plain, Figures 14 to 17--Four sections, M-N, M-P, M-R, and M-S (see Fig. 12), were

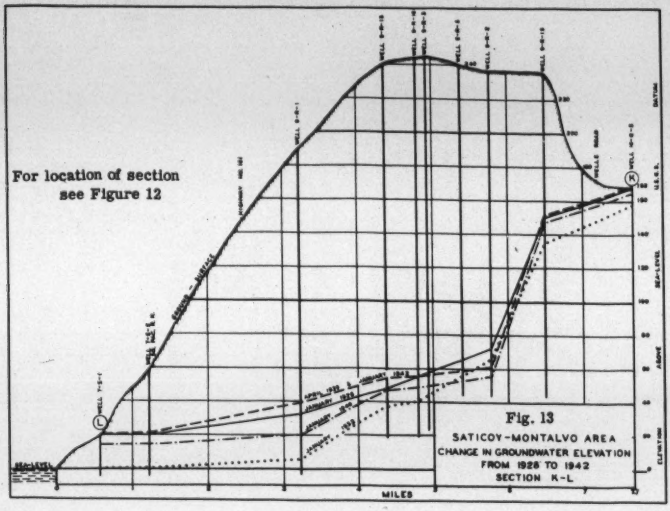

Fig. 13
SATICOY-MONTALVO AREA
CHANGE IN GROUNDWATER ELEVATION
FROM 1928 TO 1942
SECTION K-L

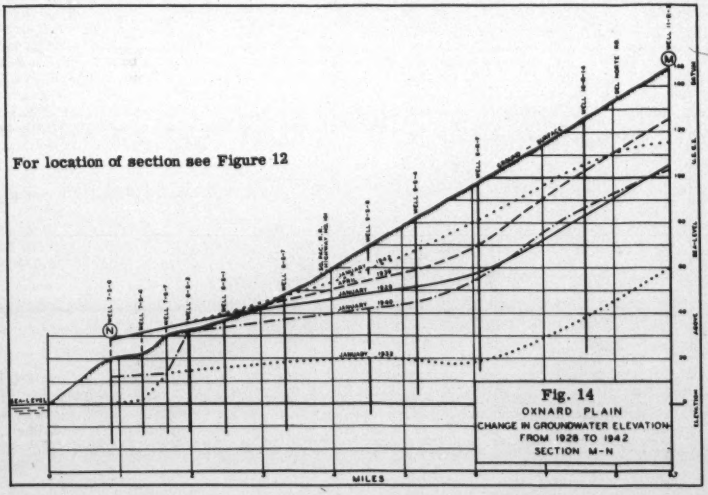

Fig. 14
OXNARD PLAIN
CHANGE IN GROUNDWATER ELEVATION
FROM 1928 TO 1942
SECTION M-N

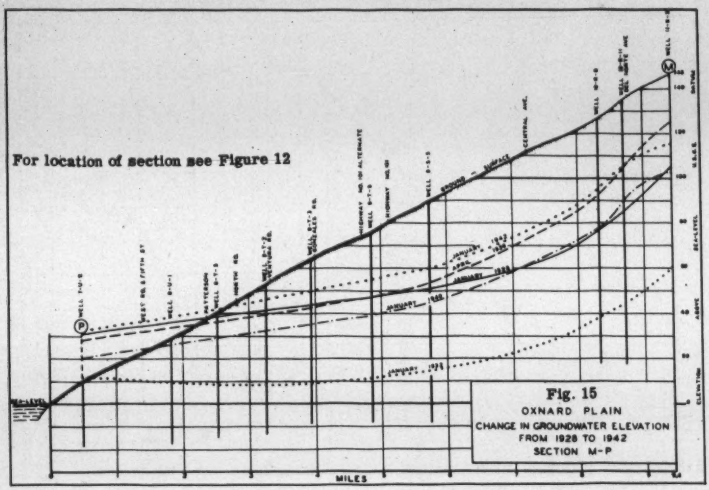

Fig. 15
OXNARD PLAIN
CHANGE IN GROUNDWATER ELEVATION
FROM 1928 TO 1942
SECTION M-P

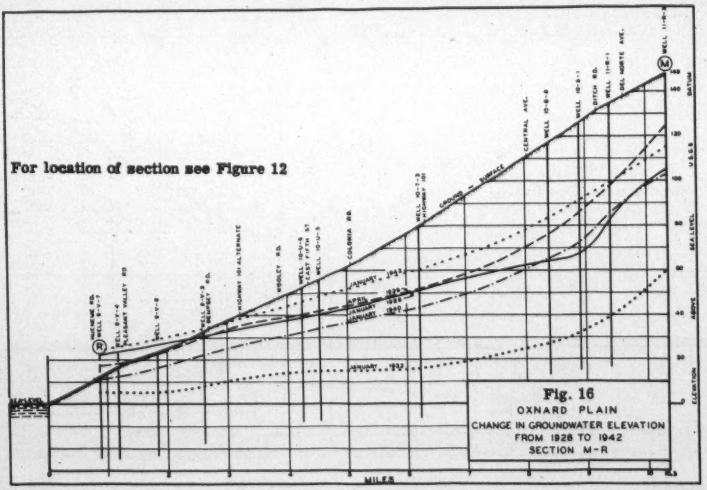

Fig. 16
OXNARD PLAIN
CHANGE IN GROUNDWATER ELEVATION
FROM 1928 TO 1942
SECTION M-R

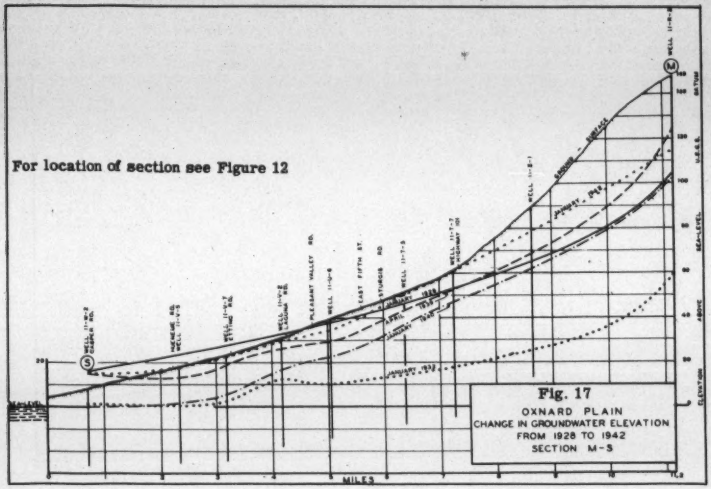

Fig. 17
OXNARD PLAIN
CHANGE IN GROUNDWATER ELEVATION
FROM 1928 TO 1942
SECTION M-S

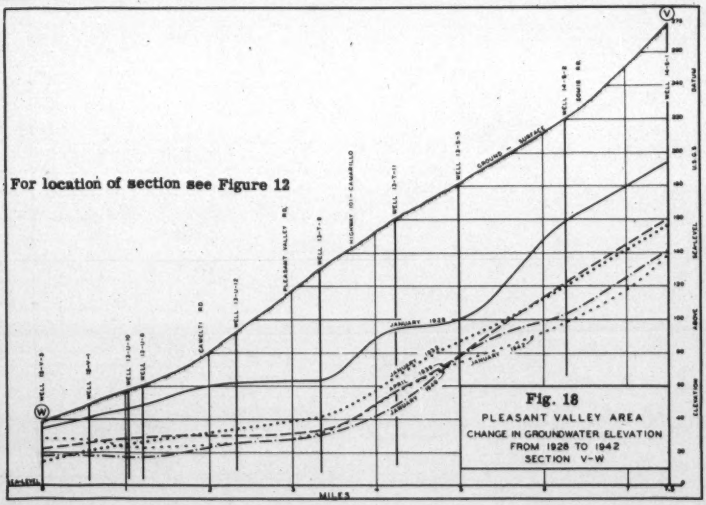

Fig. 18
PLEASANT VALLEY AREA
CHANGE IN GROUNDWATER ELEVATION
FROM 1928 TO 1942
SECTION V-W

developed to show the change in ground-water elevation in the Oxnard Plain. The profiles are shown on Figures 14, 15, 16, and 17, respectively. All sections converge at a common well in the vicinity of the Saticoy Spreading-Grounds. Wells in the area lying between Highway 101 and the ocean are under pressure. Some of these wells flow and it is possible to measure the height to which the water rises in a few of them. There was a general trend upward following the low point of January, 1932, but the high point, following the flood of March, 1938, was not reached until April,

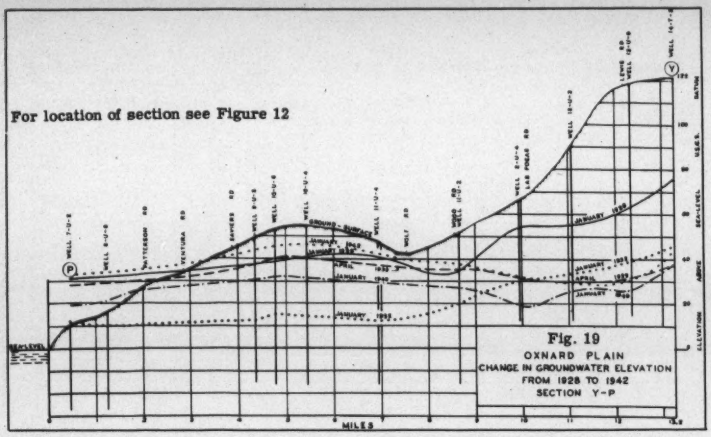

Fig. 19
OXNARD PLAIN
CHANGE IN GROUNDWATER ELEVATION
FROM 1928 TO 1942
SECTION Y-P

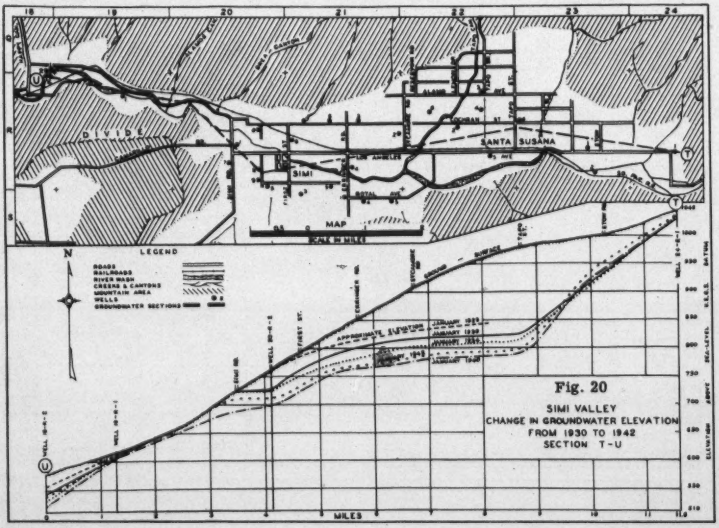

Fig. 20
SIMI VALLEY
CHANGE IN GROUNDWATER ELEVATION
FROM 1930 TO 1942
SECTION T-U

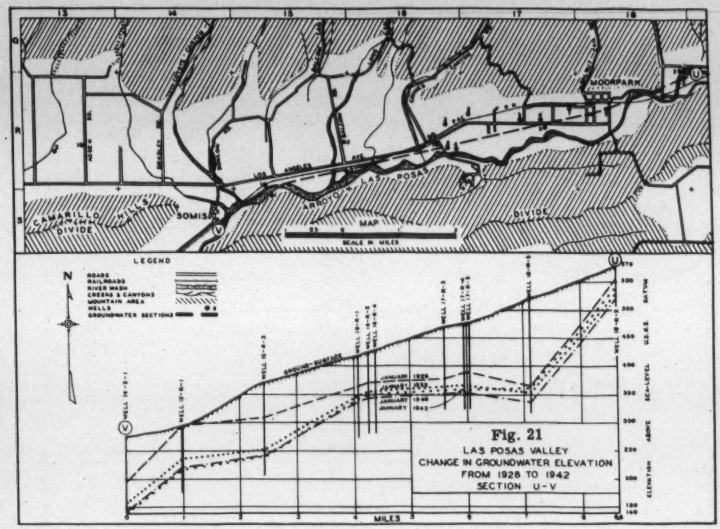

Fig. 21
LAS POSAS VALLEY
CHANGE IN GROUNDWATER ELEVATION
FROM 1928 TO 1942
SECTION U-V

1939, or just one year later than the date of the high point in the basins farther up the river. The water-plane in January, 1942, is higher than in April, 1939.

Oxnard Plain, Figure 19--This is an east-west section Y-P, Figure 12, across Pleasant Valley and Oxnard Plain. Wood Road on this section appears to be the limit of influence of the Santa Clara River.

The slope of the water-plane during the period 1928-32 indicates the ground-water is moving to the south and west. This apparent movement to the west may account partly for the rapid lowering in the Pleasant Valley Area during the same period. It is possible that the rising water-plane in the area west of Wood Road halted the flow from the Pleasant Valley Area and may account somewhat for the reduced rate of lowering of the past ten years.

Calleguas Creek Drainage-Basin

Pleasant Valley Area, Figure 18--This is a section (V-W, Fig. 12) through the Pleasant Valley Area. The general trend of the ground-water is down. It will be noted, however, that the rate of lowering during the ten-year period 1932-42 was much less than for the four-year period 1928-32.

Simi Valley, Figure 20--Simi Valley is located in the southeastern part of the county at the head of Calleguas Creek watershed. The proportion of the amount of contributing watershed to the amount of valley-lands is small. This relation in the Simi Valley is 3.2 acres of watershed to one acre of valley-lands while in the Santa Clara River Area the relation is 13.7 acres of watershed to one acre of valley-lands (see Fig. 1). Also the average rainfall on the Calleguas Creek Watershed is lower than that on the Santa Clara River Watershed. Since irrigation is practiced, these facts are reflected in the change in ground-water elevations. The general trend was down until January, 1940. The elevation of January, 1942, indicates a slight trend upward (see Fig. 20).

Las Posas Valley, Figure 21--Las Posas Valley is located in the Calleguas Creek Watershed and extends from the vicinity of Moorpark in the east end to Somis in the west end. The proportion of watershed-area to valley-lands is 3.5 acres to 1, or about the same as that of the Simi

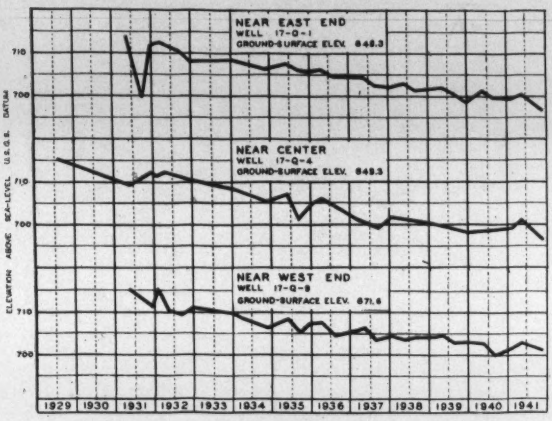

Fig. 22--Change in ground-water elevation at certain wells, Fairview Area, 1929-41

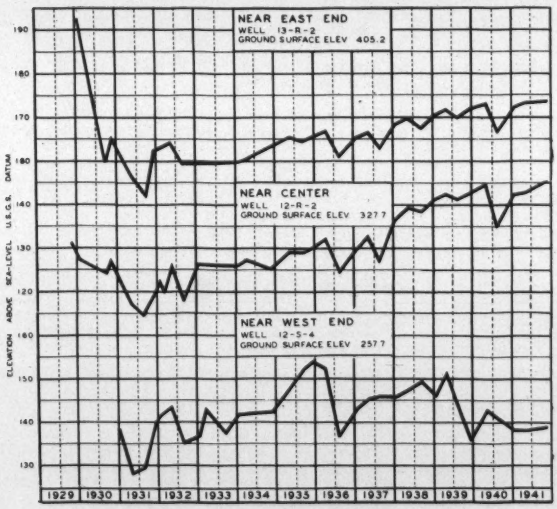

Fig. 23--Change in ground-water elevation at certain wells, West Las Posas Valley, 1929-41

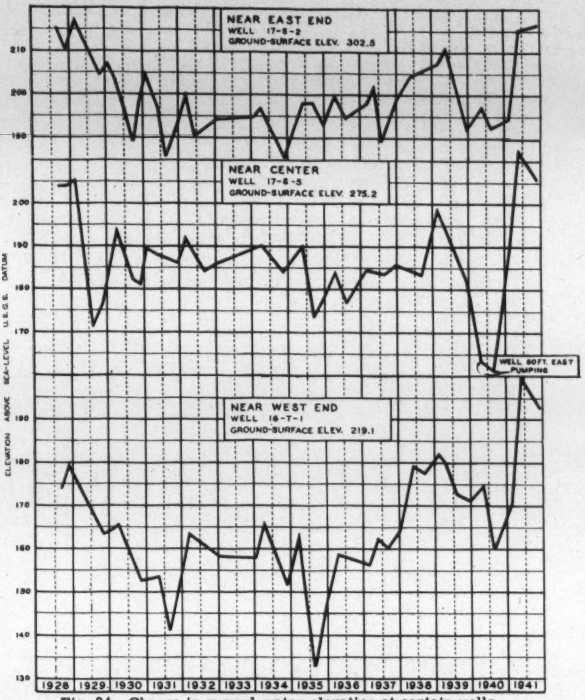

Fig. 24--Change in ground-water elevation at certain wells, Santa Rosa Valley, 1928-41

Valley Area. During the four-year period, 1928 to 1932, there was a drastic lowering of the water-plane, especially in the western portion. During the following ten years, 1932 to 1942, the average annual rainfall was somewhat higher than that of the preceding four years. This increased rainfall and the resultant decrease in pumping appears to have halted the rapid fall in the water-plane since the rate of fall during the past ten years is much less than that of the preceding four years. There was some recovery in the eastern half of the basin during 1941. A general rise of the water-plane might be expected if a wet period should occur similar to that of 1903-18 (see Fig. 2).

Fairview Area, Figure 22--The Fairview Area occupies a depression in the hills dividing the Santa Clara Valley and Las Posas Valley (see Fig. 1). The water-plane in the Fairview Area stands several hundred feet higher than the water-plane in either the Santa Clara River Valley or Las Posas Valley. The hydrographs at three wells are used to show the trend in ground-water elevation in this area (see Fig. 22). Pumping is greatest near the center of the valley.

West Las Posas Valley, Figure 23--West Las Posas Valley lies to the west of the Las Posas Valley. Water used in this area is obtained partly from wells within the area and partly from the Zone Mutual Water Company, whose wells are located in the vicinity of Somis in Las Posas Valley. There has been a general trend upward in the ground-water elevation since January, 1932, as shown by the hydrographs of three wells in the area (see Fig. 23).

Santa Rosa Valley, Figure 24--Santa Rosa Valley is located in Conejo Creek Watershed and is south of Las Posas Valley (see Fig. 1). In this valley, as in most other pumping areas, the greatest drop in the water-plane occurred in the period 1928 to 1932. From 1932 to 1938 there was very little change in the ground-water elevation. Since 1938 there has been a general trend upward until January, 1942, when the highest elevation of record has been reached. The hydrographs of three wells are shown on Figure 24.

County of Ventura,
Ventura County Water Supply,
Ventura, California

WESTERN INTERSTATE SNOW-SURVEY CONFERENCE

REPORTS AND PAPERS

JOINT REGIONAL MEETING WITH
SECTION OF HYDROLOGY OF
AMERICAN GEOPHYSICAL UNION
PASADENA, CALIFORNIA
JANUARY 16, 1942

Published August 1942

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DINNER SESSION, JANUARY 16, 1942

William A. Lang, Local Chairman, Presiding

There were 34 in attendance at the dinner and as many after-dinner guests, mainly students from the California Institute of Technology, who were interested in the military and technical aspects of the films.

MOTION FILM OF SWISS AVALANCHES

J. E. Church and A. L. Sonderegger

Since only foreign titles in German, French, and Italian accompanied the film, the picture was interpreted by Dr. J. E. Church and A. L. Sonderegger. The following explanatory titles were rendered later in English by François E. Matthes and are given in order to present the various features of the picture.

Titles of the snow-research film

(1) Investigations by the Swiss Snow and Avalanche Commission in the Parsenn region: Weissfluh ridge, 8,727 feet above sea-level
(2) The following institutions have taken part in this work:
  (a) The Mineralogic-Petrographic Department of the Federal Institute of Technology (Zurich)
  (b) The Soil Department of the Hydraulic Laboratory of the Federal Institute of Technology
  (c) The Geologic Department of the Federal Institute of Technology
  (d) The Physico-Meteorologic Observatory at Davos
  (e) The Parsenn Observation Station
  (Photographs by E. Meerkämper, Davos)
(3) Investigation of a snow-slab avalanche: The frontal Schwarzhorn avalanche across the downhill ski-course from the Weissfluhjoch to Küblis, March 30, 1937
(4) Investigations at the line of fracture
(5) Gliding sheet = disintegrated surface of ice-crust produced November 1936
(6) Internal resistance of the snow-layer (diagram of compaction)
(7) Taking snow-samples for laboratory investigation
(8) Determining plastic stretching and tensile strength
(9) Work in the field and in the laboratory
(10) Measuring the pressure of snow
(11) On a level snow-field the successive changes in each individual snow layer are closely followed throughout the winter
(12) Anemometer
(13) Trench cut in the snow in order to examine the successive layers
(14) Diagram showing progressive compaction
(15) Temperature-measurement
(16) Taking snow-samples for laboratory investigation
(17) Determining the specific gravity
(18) Cold air is blown through the snow-sample to determine its porosity
(19) Average laboratory temperature, 23° F
(20) Determining the cohesion of snow by shearing tests
(21) The plastic compressibility of snow is measured in a compression-machine
(22) The size of the snow-granules is measured by means of a vibrating sieve
(23) In the compression-machine the gradual settling of the snow is observed
(24) Measuring the creep of the snow
(25) Shear-test apparatus
(26) Snow-samples are kept in the refrigerator until their structure can be examined
(27) Preparation of thin sections for microscopic examination
(28) The orientation of the individual crystals is observed under a polarizing microscope
(29) Artificial starting of avalanches by means of trench-mortars
(30) Snow-slopes before firing
(31) Telescopic view showing line of fracture
(32) A particularly effective hit
(33) Snow-slopes after firing

The Swiss Avalanche film, which was shown previously at the International Association of Scientific Hydrology at Washington in 1939 and a copy of which was offered at cost, was purchased from the Swiss Avalanche Commission from contributions by organizations and individuals for free circulation to make snow-surveyors and mountaineers avalanche conscious and was placed in the keeping of the International Commission of Snow and Glaciers to assure widest circulation even in foreign countries after the war is over. It has now had a long circuit through Nevada, Utah, Oregon, California, to Chicago, Baltimore, and Washington, D. C., and has been shown by the Forest Service, National Park Service, Snow-Survey Conferences, Mountain Clubs, Academies, and Universities. Requests have been received for showing next autumn in Colorado, Washington, Wyoming, and California. The film has been copied by the Army and the Forest Service. English titles will be substituted for the foreign and possibly a sound-track may be employed. Illustrations from the little handbook "Lawinen" have been released by the Swiss Glacier Commission for use in publications on avalanches in America.

Large credit is due to the Swiss government that forwarded the film from Switzerland to America in the diplomatic mail pouch and to General Secretary John A. Fleming who then forwarded the film by air-express to Pasadena in time for first showing at the dinner meeting.

SOUND-COLOR-FILM OF SUN VALLEY SNOW-SPORTS

Union Pacific Railway

This film was loaned by the Union Pacific Railway. It provided a vivid picture of snow-sport and transport.

COLOR-FILM ON SNOW-SCENES AND SNOW-SURVEYING IN THE CENTRAL SIERRA

Walter J. Herz

This film by Walter J. Herz was shown at the noon luncheon of the Section of Hydrology and Western Interstate Snow-Survey Conference, January 16, 1942.

ADDRESS OF WELCOME

Franklin Thomas

The Snow-Survey Conference was cordially welcomed by Professor Franklin Thomas, local Chairman of the Regional Meeting of the Section of Hydrology of the American Geophysical Union and representative of the California Institute of Technology, who emphasized the growing field and importance of snow-surveys and their application.

ROUND-TABLE REPORT OF FORECASTERS AND COMPARISON OF FORECASTS OF RUNOFF AND ACTUAL RESULTS FOR 1941

CALIFORNIA FORECASTS FOR 1941

Fred H. Paget

The forecasts of stream-flow made in California from the snow-survey data on April 1, 1941, and as amended on May 1 because of excessive precipitation in April, were very satisfactory. Out of 26 forecasts made and published, 20 came within ten per cent of the actual runoff, three had a divergence of 11 to 15 per cent, while three had a divergence of from 16 to 20 per cent. Table 1 gives the actual figures for each of the main watersheds and main tributaries.

Table 1

Drainage-area or stream-gaging station	Stream-flow April 1 to July 31			
	52-year normal 1890-1941, acre-feet	Forecast for 1941, acre-feet	Actual flow in 1941, acre-feet	Discrepancy in per cent
South Fork Pit River near Likely	40,000	29,000	31,500	- 8
Pit River near Ydalpom	1,272,000	1,400,000	1,339,800	+ 5
Sacramento River at Kennett	2,027,000	2,600,000	2,882,100	-10
Feather River near Oroville	2,288,000	2,100,000	2,562,900	-18
Bowman Area-Middle Yuba and Canyon Creek	99,000	132,000	141,200	- 7
South Fork Yuba River at Lang's Crossing	246,000	275,000	281,613	- 2
Yuba River at Smartsville	1,231,000	1,200,000	1,456,975	-18
North Fork American River near Colfax	316,000	290,000	302,750	- 4
Middle Fork American River near Auburn	701,000	580,000	599,400	- 3
American River at Fairoaks	1,566,000	1,300,000	1,531,000	-15
North Fork Mokelumne River near West Point	469,000	510,000	531,700	- 4
Mokelumne River near Mokelumne Hill	545,000	560,000	576,400	- 3
Middle Fork Stanislaus River near Avery	390,000	440,000	445,000	- 1
Stanislaus River below Melones P. H.	846,000	950,000	931,400	+ 2
Tuolumne River near Hetch Hetchy	683,000	900,000	844,600	+ 7
Tuolumne River at La Grange	1,368,000	1,900,000	1,706,500	+11
Merced River at Pohono Bridge	423,000	625,000	534,830	+17
Merced River at Exchequer	723,000	1,050,000	955,800	+10
Big Creek at Huntington Lake	111,000	150,000	146,224	+ 3
South Fork San Joaquin River at Florence Lake	218,000	310,000	294,000	+ 3
San Joaquin River above Big Creek	1,195,000	1,600,000	1,628,600	- 2
San Joaquin River at Friant	1,400,000	1,950,000	1,926,000	+ 1
North Fork Kings River below Rancheria Creek	332,000	440,000	394,860	+12
Kings River above Piedra	1,376,000	1,950,000	1,901,400	+ 2
Kaweah River near Three Rivers	301,000	440,000	445,250	- 1
Kern River near Bakersfield	482,000	930,000	1,008,300	- 8

Division of Water Resources, California Department of Public Works, Sacramento, California

SNOW-FORECAST, MOKELUMNE WATERSHED

L. Standish Hall

The precipitation on the Mokelumne Watershed above Pardee Reservoir during the past season, 1940-41, averaged 49.53 inches, or 112 per cent of normal. The seasonal precipitation was 94 per cent of that occurring during the seasonal year 1939-40 when the average for the watershed was 52.66 inches. In the early part of the present season the precipitation was deficient. However, heavy rains in December brought the total well above normal. During the subsequent months the precipitation was not quite as heavy as during the month of December, but was still of sufficient quantity to maintain the total above normal through the remainder of the season.

Observations in the high mountains showed that snow first accumulated on the ground on November 2, or 25 days earlier than in 1939. However, this fall was very light and melted in a short period of time. The first permanent snow-accumulation started on December 16. Through

the last half of December and until the last week in January, the accumulation of snow was continuous with only a few short intermissions. The month of February was relatively clear and cold, permitting the snow to pack. Early storms in March added to the snow-pack, while early storms in April brought the depth of snow on the ground at the higher ranges to the maximum for the season.

A peculiar feature of the winter's precipitation was that in the central portion of the Sierra Nevada, centering around the Mokelumne River, the precipitation was only slightly above normal. In contrast, on the northern and southern ranges and on the coastal areas the precipitation for the season was the heaviest that had been recorded in many years. The winter temperatures in the high mountains were moderately cold, with the result that little melting occurred so that on the Mokelumne Watershed the snow-pack on April 1 was 104 per cent of normal, or 110 per cent more than the snow-pack of the previous year. Results of the snow-survey released by the California Cooperative Snow-Survey on April 1 gave the data for the Mokelumne snow-courses.

As in the previous year, estimating of runoff from melting snow for the period from April to July was complicated by the occurrence of a heavy storm during the last three days of March and subsequent to the measurement of many of the snow-courses. Including 1.34 inches of precipitation that fell as rain or snow during the last three days of March, the total for the period from April to June was 8.67 inches, or nearly three inches in excess of the normal for the period. As a result, an upward revision of the estimate for April 1 was indicated.

As in the preceding year, there was but very little snow on the ground below the 6,000-foot elevation on April 1, and again the measured runoff exceeded the estimate by a large amount. It would appear that the distribution of the snow-courses is not satisfactory to obtain a true total of the snow on the ground in certain years. Fred H. Paget, Engineer in Charge of the California Cooperative Snow-Survey, made an estimate of the runoff, based solely on the results of the water-content of the snow at six of the stations at elevations above 6,000 feet. His original estimate predicted the runoff of 550,000 acre-feet, which on May 1 was increased to 560,000 acre-feet, due to the increased precipitation. The estimate of snow-runoff, based on the stations at the higher altitudes, has resulted in a closer agreement with the actual measurements during the past two years, although in previous years such close agreement was not obtained by this method.

The estimate of runoff from melting snow was prepared by the Hydrographic Division by the method used in the previous years.

The total water-content of the snow on the ground above the 4,000-foot elevation divided into various zones of equal elevation is 523,600 acre-feet.

Using the relation of percentage of total water-content of the snow appearing as runoff determined in previous years, it was estimated that the total runoff from snow during the current year would be 460,000 acre-feet. On May 1, because of the heavy precipitation during the month of April, this estimate was increased to 500,000 acre-feet. Making allowances for the probable variation which might exist in the rainfall during the period that the snow was melted, a variation of 75,000 acre-feet either greater than or less than the above figure might be expected. The actual runoff during the period from April to July was 579,000 acre-feet, or 110 per cent of the total water-content of the snow on the ground on April 1.

The cold weather in the mountains delayed the melting of the snow considerably beyond the period of 1940. In the previous year the river had reached its normal summer discharge by June 20. However, in 1941 during the month of April, only 105,000 acre-feet of the snow-runoff had been measured at station near Mokelumne Hill. The melting of the snow proceeded at a relatively slow rate with the result that even on June 21 there remained a considerable depth of snow on the ground at the higher altitudes. The river did not reach its normal summer regimen until July 12.

The comparison of the records for the past seven years is shown in Table 1.

During the years 1940 and 1941 the difference in the results obtained between the actual runoff and the estimated runoff by the quantitative method has been entirely out of line with the results which had been obtained in previous years. The results of the past two seasons are consistent between themselves and indicate an increase in the percentage-runoff of melting snow of 25 per cent greater than the results obtained from the five previous years of record. No satisfactory explanation of this discrepancy can be made up to the present time beyond those mentioned in the report of the previous year [Trans. Amer. Geophys. Union, 1941, p. 141].

Table 1--Comparison of snow on ground above 4,000-foot elevation on April 1, and subsequent runoff from melting snow, together with factors affecting runoff, Mokelumne Watershed

Year	Total water-content of snow, April 1	Average water-content of snow on ground, April 1		Natural runoff near Mokelumne Hill, April to July	Runoff as per cent of water-content of snow, April 1	Mean rainfall on Watershed April to June
		Above 4,000 ft	Above 6,000 ft			
	acre-feet	inch	inch	acre-feet	per cent	inch
1935	584,000	27.4	34.3	556,000	95.2	13.17
1936	675,000	31.7	42.5	581,000	86.1	7.10
1937	680,000	31.9	41.7	514,000	75.5	3.66
1938	948,000	44.5	56.8	812,000	85.6	6.55
1939	278,000	13.1	22.5	212,000	76.2	4.12
1940	495,000	23.2	40.6	497,000	100.4	3.48(a)
1941	524,000	24.6	40.1	579,000	110.5	8.67(b)

(a) = 1.60 inches of precipitation, March 31, included in April record.
(b) = 1.34 inches of precipitation, March 29-31, included in April record.

East Bay Municipal Utility District,
Oakland, California

RUNOFF TRIBUTARY TO STORAGE-RESERVOIRS ON UPPER SAN JOAQUIN RIVER

William A. Lang

The Edison Company's Big Creek hydroelectric development is served by three storage-reservoirs, namely, Huntington, Florence, and Shaver lakes, having a combined capacity of 288,523 acre-feet. These three reservoirs impound the runoff of Bear Creek, Mono Creek, South Fork San Joaquin River, Big Creek, Pitman Creek, and Stevenson Creek. The combined area of the six drainage-basins is 450 square miles, 45 per cent of which is above an elevation of 10,000 feet.

Using the direct method of forecasting, we predicted a runoff of 836,000 acre-feet on March 1, 1941, and a runoff of 745,000 acre-feet on April 1, 1941. The actual runoff received between November 1 and July 31 was 810,000 acre-feet, indicating an error of +3.2 per cent as of March 1 and an error of -8.0 per cent as of April 1 for our forecasts for 1941.

Southern California Edison Company, Ltd.,
Los Angeles, California

CENTRAL SIERRA QUADRANGLE, EASTERN SLOPE

H. P. Boardman

Basin	Normal		Forecast			Actual			Divergence, per cent normal
	Rise April 1 to high water	Runoff	Per cent normal	Amount		Amount		Per cent normal	
				Rise	Runoff	Rise	Runoff		
	ft	ac-ft		ft	ac-ft	ft	ac-ft		
Tahoe	1.68	.....	75.0	1.26	.....	1.56	.....	92.9	+17.9
Truckee (exclusive of Tahoe)	.....	325,700	79.8	.....	260,000	.....	279,200	85.7	+ 5.9
Carson at Fort Churchill	.....	230,000	76.1	.....	175,000	.....	174,866	76.03	- 0.07
West Walker near Chris Flat	.....	191,200	97.8	.....	187,000	.....	190,230	99.5	+ 1.7
East Walker at Bridgeport Dam	.....	73,000	91.8	.....	67,000	.....	90,460	123.9	+32.1

In partial explanation of the relatively large excess runoff over forecast for the Tahoe and East Walker basins: A number of Weather Bureau stations in the Central Sierra recorded precipitation much above normal in April and several snow-survey courses had a considerably higher water-content May 1 than April 1.

Very likely excess precipitation occurred during the runoff period on the East Walker Basin. Two and one-half inches over the 183 square miles above 7,000-foot altitude on this watershed would more than equal the difference between the forecast and the actual runoff. There are no Weather Bureau precipitation-stations nearer to this 183 square miles than Bridgeport Dam, 6,400-foot altitude, where the precipitation is very small in amount.

Nevada Cooperative Snow Surveys,
Reno, Nevada

THE HUMBOLDT BASIN, NEVADA: TWO UNUSUAL YEARS, 1940-41 AND 1941-42

J. E. Church

The report on the divergence between forecast and runoff of the Humboldt River during 1940-41 made at the Pasadena Meeting in January was followed so quickly by the unusual experience of 1941-42 that it was decided to expand the original report to include the two seasons. This is particularly desirable since the regional meeting at Salt Lake City arranged for June has been abandoned. The two seasons also blend into and supplement each other, thus making a desirable unit.

The past and present years have brought surprises as great as Pearl Harbor but have revealed the power of moderate precipitation or temperature when prolonged or combined with other factors. The experience will ultimately provide increased foresight and accuracy. The tables will furnish desirable data for comparison and a foundation for conclusions.

During the preceding seasons of 1938-39 and 1939-40, the divergence between forecast and runoff was only 4.6 and 4.3 per cent of normal, respectively, with a snow-cover March 1 of 69.4 and 56.0 per cent. The winter and summer flow at Palisade for both seasons was also below normal and the ground-water level as shown by wells in Lamoille and Elko valleys was relatively low.

Season of 1940-41--The snow-cover of 1940-41 on March 1 and the attending winter runoff were similarly low, being 71.4 and 64.2 per cent of their respective normals. The ground-water level was much lower than on any previous year of measurement except 1940 in Elko Valley.

During March, the initial month of the runoff-season and the index of its trend, the precipitation was below normal and the temperature slightly above (departure +1°.4 F). The runoff at Palisade was 50.9 per cent of its monthly normal or 20.5 per cent of normal below the snow-cover of March 1 and 7.7 per cent below the snow-cover of April 1. Therefore, a confident forecast was made of a probable runoff during March to July of 60 per cent or 150,000 acre-feet.

The temperature during the season remained relatively low but the precipitation increased to double normal during April and even throughout April to June, when most effective on the snow, and produced a total runoff for March to July of 271,500 acre-feet, leaving an excess of 121,500 acre-feet or 48.6 per cent of normal above the 150,000 acre-feet forecasted.

This trend was realized by May 1 but even then only 40,000 acre-feet was added to the forecast, leaving it still 32.6 per cent below the actual. This was inevitable, for there was no means of knowing that the excessive rains would continue.

This result was due to snow-accumulation on the high watersheds as well as to the detouring of the water around the meadows because of surplus rain, which decreased the necessity for heavy irrigation. The former is shown by the heavy flow in Lamoille and Martin creeks at their canyon outlets above diversions.

In the comparison, the snow-cover of April 1 has been chosen as a more substantial basis than the adjusted forecast. The snow-cover of March 1, which is the starting point of all estimates of the flow during March to July, may be even more desirable for the purpose.

It will be noticed that the excess of the main upper Humboldt at Palisade affected by heavy irrigation-diversions is scarcely more than that of the mountain streams, Lamoille and Martin creeks, measured above practically all diversions.

The Utah rivers likewise exceeded their forecasts. The Sierra Nevada streams, however, conformed to their snow-cover for they were outside of the belt of excessive rain.

Table 1--Comparison of snow-cover and runoff, 1941, per cent of normal

Basin	Snow-cover April 1	Runoff March to July	Excess
Humboldt River at Palisade	58.6	108.6	50.0
Lamoille Creek	72.1	121.0	48.9
Martin Creek in Little Humboldt Basin	87.6	129.8	42.2

The rains continued into the winter, building up an unusual stream-flow and ground-storage destined to affect materially the runoff of the succeeding season.

Table 2 shows the gradual build-up of runoff in the upper Humboldt during the season. The snow-cover March 1 (approximately 75 per cent of normal) is used as a base. The temperature-departure from normal at Elko and the deficiency or excess of precipitation at United States Weather Bureau stations in the area are given as major controlling factors. The runoff is measured at Palisade.

Table 2--Monthly build-up of runoff in Upper Humboldt at Palisade, 1941 into 1942

Month	Per cent expected runoff based on snow-survey March 1	Normal runoff	Forecast runoff	Temp. dept. from normal	Deficiency or excess precip.	Actual runoff	Gain or loss in forecast	Accumulated surplus runoff
		ac-ft	ac-ft	°F	pct	ac-ft	ac-ft	ac-ft
Mar.	75	40,940	30,700	+1.4	- 50.7	20,850	- 9,850	- 9,850
Apr.	75	56,400	42,300	-4.1	+100	45,000	+ 2,700	- 7,150
May	75	63,500	47,600	0.0	+ 66	77,000	+29,400	+ 22,250
June	75	69,200	51,900	-4.4	+134	103,000	+51,100	+ 73,350
July	75	25,600	19,200	-0.9	- 50	27,700	+ 8,500	+ 81,850
Aug.	100[a]	4,720	4,720	-2.8	+149	7,500	+ 2,780	+ 84,630
Sep.	100	2,660	2,660	-6.3	+ 62.7	3,430	+ 770	+ 85,400
Oct.	100	4,450	4,450	-2.9	+ 71	5,750	+ 1,300	+ 86,700
Nov.	100[b]	6,020	6,020	0.0	+ 22	10,930	+ 4,910	+ 91,610
Dec.	100	6,780	6,780	+4.7	+ 64	16,490	+ 9,710	+101,320
Jan.	100	8,310	8,310	+0.8	- 18	16,550	+ 8,240	+109,560
Feb.	100	15,810	15,810	-5.5	- 5.5	20,270	+ 4,460	+114,020

[a]Since the dominant effect of the melting snow-cover has now disappeared, the forecast must be based on coincident rain, which must be considered as normal.

[b]Based on precipitation and melting at lower levels, for during the winter the snow at higher levels merely accumulates.

The heavy build-up of runoff during June seems to be the result of low temperature and high precipitation during April that was only partially released in May and the even heavier precipitation of June. Because of the increasing warmth of the season, the negative temperature-departure in June is less effective in staying melting than in April.

The accumulation of April to June evidently maintains its effect through July, which is deficient in current precipitation.

The build-up of the runoff continues during the summer-autumn months of August to October and even through the winter months of November to February. The rainfall during August to October augmented the runoff and possibly the rain-snow of November to February had a similar effect. Increasing soil-moisture and decreasing absorption, shown by the rise of the wells in December of more than a foot above the level of the preceding season, is probably the dominant agency.

The departure in temperature after the disappearance of the snow-cover has little effect on runoff. This is likewise true in the depth of winter. Quantitative measurements of rainfall are omitted in favor of percentage since the available stations can indicate only trends and not total quantity over the basin. The average of the percentages for April to July or even for April to October, if weighted according to the relative monthly precipitation upon which they are based, should provide a key to the season's excess runoff.

Season of 1941-42--The season of 1941-42 is the extension of the factors prevailing the

previous year accentuated by the accumulation of low-level snow from cold and its sudden melting by high temperature, which came unexpectedly after the season's trend seemed established.

Flood-years are rare and no stream-measurements were ever made of the destructive flood on the Humboldt in 1910, which is comparable to the present and has been described elsewhere [Trans. Amer. Geophys. Union, 1940, pp. 966-967]. This flood too, as pointed out by H. P. Boardman, may have been accentuated by a water-table evidently built up during the preceding years of 1906-09, when the annual precipitation for the calendar year (measurements based on 10 to 13 stations) was 136, 149, 92, and 136 per cent, respectively. The precipitation during November to February, 1909-10, immediately preceding the flood, was 168 per cent.

Although the precipitation of the summer and autumn of 1941 was quantitatively small, its excess above normal was 92.4 per cent, and 43.0 per cent for the first half of the winter. The resulting ground-water, shown by well-measurements in Elko and Lamoille valleys, continued to build up until it rose 3.7 feet from minimum to maximum within the short period of a year. The winter runoff at Palisade kept pace and exceeded normal for the first time since 1923-24, attaining 140.2 per cent of normal. That this was not true also of Martin Creek is due possibly to the smallness of the stream and its susceptibility to freezing.

On March 1 the snow-cover was 89.9 per cent of normal and on April 1, 83.9 per cent, while the low-level snow retained at the latter date a percentage of 77.7. March was cold (temperature-departure -2°.7 F at Elko and -3°.8 F at Lamoille) and the precipitation was 53.6 per cent deficient, yet the runoff for the month was 126.5 per cent of its normal, indicating evidently ground-water effects. Although the low-level snow-cover was within ten per cent of the high-level of March 1 and snow in mid-March was heavy in the foothill meadows of the tributaries of the Humboldt, the low snow at snow-survey stations was but little in excess of that of 1940-41 and did not occur at all in the lower Humboldt at Austin and Paradise Valley, which have been indexes to previous floods.

But the sudden rise in temperature in early April to 12°.0 F above normal (as measured at Lamoille) and its continuance at +6°.0 F during the following two weeks caused a runoff at Palisade for the month of 152,000 acre-feet and flooded lowlands along both the upper and lower Humboldt. The temperature-departure at Elko during the first three weeks, however, was only +3°.0 F and fell to -1°.5 F for the month. The precipitation was 132.0 per cent of normal or one-third in excess.

The excessive runoff noted at Palisade prevailed also in the Little Humboldt Basin as also in North Fork and Secret Creek and on the lower portions of Marys River, Lamoille, and South Fork. High water was reported along the foothills on both slopes of the Continental Divide.

In Martin Creek of the Little Humboldt Basin the runoff as measured April 1 to 12 was 280 per cent of normal. The precipitation for the entire month in this basin was 162.8 per cent. In contrast, because of its high elevation, the upper Reese River Basin adjoining it on the south had no high water at all.

The runoff at Palisade May 1 to 16 (at the time of writing) is already 51,800 acre-feet or 81.5 per cent of the normal for the entire month. The precipitation at Lamoille is 72.2 per cent and the temperature -5°.5 F.

The snow-cover in Lamoille Canyon at elevations of 8,500 and 9,000 feet is slightly more than on March 1 and at the latter elevation is 109.8 per cent of the normal for March 1. However, the snow at 7,400-foot elevation and below is gone and the higher areas are small.

Forecast for Upper Humboldt Basin--The following factors enter into the final forecast:

(1) Snow-cover March 1, 89.9 per cent = runoff at Palisade	225,000 acre-feet
(2) Precipitation to date (May 20, 1942), 86.9 per cent	
(3) Temperature at Lamoille for March -3°.8, for April +6°.3, for May -5°.5F	
(4) Gain in flow from ground-storage in five months	25,000 acre-feet
(5) Accumulation through excess flow over forecast (solely on basis of 1913-14 at Palisade, due, however, to winter precipitation 132.0 per cent, summer precipitation approximately 130 per cent, and temperature in March +2°.0F)	100,000 acre-feet
Total	350,000 acre-feet

Of the accumulation in 1913-14, 50,000 acre-feet more than indicated by precipitation-records was recorded at Palisade during March, when the rain was light (22.1 per cent) and the temperature was high (+2°.0 F). The balance (50,000 acre-feet) occurred during April to July while the mean temperature was below normal but the precipitation was high (159.1 per cent). Therefore, only the 50,000 acre-feet of March can be considered a positive index of relative flow the present year. Unlike 1940-41 the excess is coming wholly from the floor of the basin and the flow should gradually decline to approximately the percentage of the snow-cover. The fall in temperature will tend to postpone the flow.

A view of the high Humboldt River and white neighboring mountains from the train in early June indicated that the stream would provide the runoff of 90 per cent predicted in addition to the flood-flow of April.

The factor of excess temperature acting on excess accumulation of low-level snow is evidently delicate in its balance but powerful. In the present season it was abetted by unusual soil-moisture. The latter can be readily observed but must be isolated from the temperature-factor before its effectiveness can be quantitatively determined. It is unfortunate where factors cannot be controlled that the unusual occurs so seldom.

Nevada Agricultural Experiment Station,
Reno, Nevada

COLUMBIA, KOOTENAY, AND OKANAGAN BASINS AND THE COASTAL BELT ADJACENT TO VANCOUVER

S. H. Frame

On April 1, 1941, the snow-cover from the Coast to the Interior was considerably less than the average depth of previous years. The depth of water in the snow was 50 per cent of the normal for the Columbia, Kootenay, and Okanagan basins, and about 60 per cent of that for the Coastal areas. Owing to this abnormal lightness of snowfall, it evidently was difficult to get a true water-content, as compared to that secured from the snow-cover of an average winter. This is borne out by the fact that for practically all stations the forecasts were too low.

The average precipitation during April to August for ten representative interior stations was 133 per cent of normal, or a third greater than usual, thus more than balancing any lack of runoff from the snow-cover. In the Coastal area, the average of seven stations showed the precipitation was five per cent above the normal.

Table 1 gives a summary showing the forecasted and actual runoff in acre-feet, with percentages of error from the actual. Table 2 gives the summer precipitation in per cent of normal.

Table 1--Forecast and actual runoff

Main river-basin	Tributary basin	Stream		No. of courses involved	Runoff				
		Name	At		Forecast, acre-feet	Per cent normal	Actual, acre-feet	Per cent normal	Error in per cent of actual
				Coastal					
Fraser	Stave	Stave	Stave Falls	3	.....	.....	777,000	75.6	.....
Powell	.....	Powell	Powell Lake	2	489,700	55.8	766,200	87.8	-36.1
				Interior					
Columbia	Kootenay	Lardeau	Gerrard	1	363,700	74.0	402,800	84.1	- 9.7
Columbia	Kootenay	Duncan	Howser	1	1,723,700	97.0	1,553,000	88.3	+11.1
Columbia	Kootenay	Elk	Elko	2	552,000	46.7	578,100	49.9	- 4.5
Columbia	Kootenay	Slocan	Crescent	1	403,200	23.8	1,281,000	77.7	-68.5
Columbia	Kootenay	Kootenay	Wardner	3	1,610,000	41.2	2,527,000	65.5	-36.3
Columbia	Kootenay	Kootenay	Glade	5	7,460,000	48.1	10,164,000	66.4	-26.6
Columbia	.....	Columbia	Golden	3	1,244,000	58.7	1,533,000	73.0	-18.9
Columbia	.....	Columbia	Revelstoke	6	9,816,000	54.9	15,511,000	87.2	-36.7
Columbia	.....	Columbia	Trail	14	18,991,000	51.9	28,647,000	76.4	-33.7
Okanagan	Okanagan	Okanagan	Penticton	5	135,530	46.1	207,470	74.2	-34.7

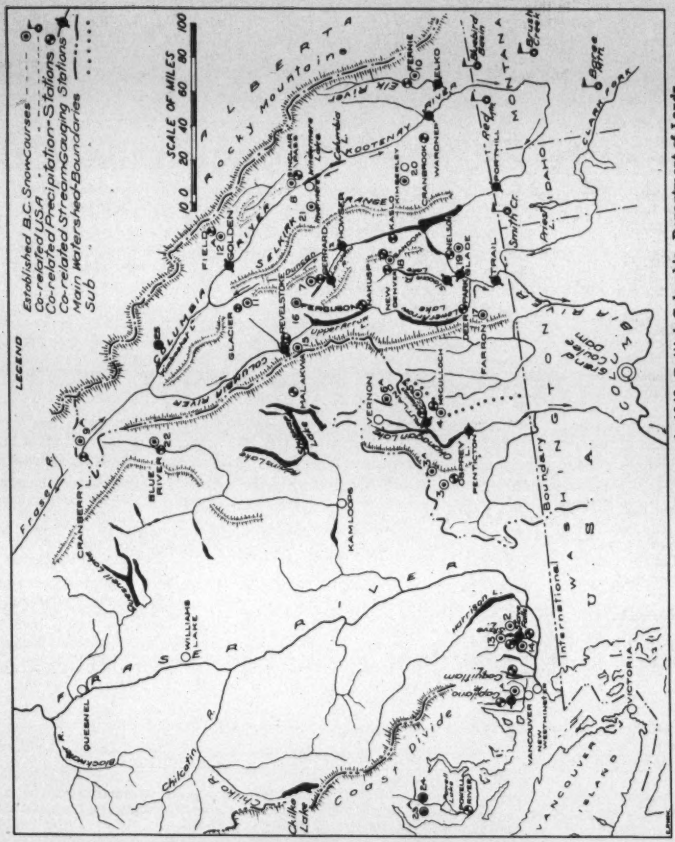

Fig. 1--Snow-survey system as on January 1, 1942, British Columbia, Department of Lands, Water-Rights Branch

Table 2--Precipitation in percentage of normal

Station	Per cent of normal April-July	Station	Per cent of normal April-August
Coastal		Interior	
Powell River	133	Field	77
Lois River	120	Glacier	107
Capilano	98	Cranberry Lake	172
Crouse Mt.	85	Revelstoke	115
Stave Falls	102	Nakusp	140
Stave Lake	109	New Denver	163
Hope	91	Deer Park	173
		Fernie	88
Interior		Kaslo	120
McCulloch	179	Nelson	174
Osprey Lake	185	Blue River	97

Coastal Area--In this area there were three courses which did not show any snow at the end of March, while two others gave a very low water-content. The water-content of the Powell River area expressed in the per cent of normal of the runoff during April to July was 56 per cent, the actual runoff being 87 per cent or practically one-third more than was forecasted. The precipitation during April to July was 26 per cent above normal which would tend to make up the forecast deficiency.

In the Vancouver and Stave Lake areas, similar conditions prevailed. The actual runoff during April to July from the Stave Lake Watershed was 76 per cent of normal. No forecast was made. The above-normal precipitation for the same months obviated there being any shortage of water.

Okanagan Basin--The forecast for this basin was 46 per cent of the average runoff during April to July, the actual runoff being 74 per cent or about one-third greater. There was an above-normal precipitation for the same months of 86 per cent.

Kootenay-Columbia Basin--In this basin the forecast was for 55 per cent of the normal for April to August, the latter covering periods of from seven to 27 years. Over the whole area the precipitation for the same months was 130 per cent of normal.

East Kootenays--The prediction for the Elk and Kootenay (at Wardner) rivers in this area was for 44 per cent of the runoff during April to August. The actual runoff was 58 per cent of the same normal or 14 per cent more than the forecast. The rainfall during April to August, as recorded by the two nearest precipitation-stations, was 30 per cent above normal, showing 72 per cent above on the Kootenay Watershed and 12 per cent below on that of the Elko.

North Kootenay Area--The forecast for the Lardeau and Duncan rivers in this area was for 85 per cent of the normal runoff during April to August. The actual runoff was 86 per cent of the same normal, the prediction being within one per cent. The precipitation during April to August for these watersheds was slightly above normal.

West Kootenay and Arrow Lakes Area--The forecast for the Slocan and Kootenay (at Glade) rivers was for 36 per cent of the runoff during April to August. The actual runoff was 72 per cent of the same normal, or twice as much as the prediction. The rainfall of April to August, as recorded at the two nearest precipitation-stations, was 73 per cent above normal, and that for the area near the source of the Slocan River was 63 per cent of normal.

Columbia Basin--The water-content in the snow-cover in this basin gave a forecast of 55 per cent of normal for the runoff during April to August. The actual runoff was 78 per cent of the same normal which is 23 per cent more than the prediction. The precipitation of April to August in the basin, as recorded at a number of stations, shows an average of 154 per cent of normal.

Conclusion

It will be noted that, with the exception of the North Kootenay Area, the forecasts were considerably below the runoff which actually occurred. It will also be noted that the precipitation for the summer months was very much above normal, excepting that for the North Kootenay.

In making a study of all the forecasts, it would appear that, had not the summer runoff been augmented by such an abnormal precipitation, the forecasts would have approached very closely to that expected from a normal runoff during April to August.

Water Rights Branch, Department of Lands,
Victoria, British Columbia

SNOW-SURVEY EQUIPMENT

WINTER TRANSPORTATION IN THE HIGH SIERRAS BY "SNO-MOTOR"

P. H. Ducker

The problem of winter transportation to important reservoirs and river-diversion structures owned and operated by the Southern California Edison Company, Ltd., in the snow-bound High Sierras appears to be quite successfully solved by a crawler-type "Sno-Motor" designed by T. P.

Flynn, Senior Equipment Engineer of the United States Forest Service, and built by the Monarch Forge and Machine Works of Portland, Oregon.

The Southern California Edison Company's Florence Lake Reservoir and Dam, and the Mono Creek and Bear Creek diversion-facilities lie on the other side of a 10,000-foot mountain range from the rest of the Company's Big Creek-San Joaquin River hydroelectric development. Part of these facilities, principally the underground conduits, were constructed from self-sustaining camps, having hospitals and medical personnel, and worked all the year around by warehousing sufficient materials and supplies to operate eight months out of the year without any outside assistance whatsoever. The remainder of these facilities, consisting of dams and pipelines, were constructed by seasonal operations that were closed down during the severe winter months. All requirements of transportation for construction were taken care of during the summer months, when the roads were open, with regulation mountain trucking equipment, and did not present any unusual transportation-problems.

The operation and maintenance of these facilities after the period of construction was over presented an entirely different problem, namely, the transportation of men and materials, from one location to another throughout the winter, the collection of records, measuring and regulating stream-flows, and providing the necessary maintenance to keep these properties in good operating condition. These snow-bound facilities were only accessible by skis or snowshoes for more than six months out of the year prior to the purchase of the "Sno-Motor." This isolation carried with it the danger of accidents, illness, and the problem of economically storing small quantities of perishable supplies for the entire winter period.

The "Sno-Motor" eliminates the worry over sickness and accident for the personnel required to operate these facilities, and permits the safe, dependable transportation of men, food, materials and supplies, and repair parts during the winter. It is also of assistance in repair work and snow-survey work.

This machine looks like an old-style army-tank attached to a sea-sled. It will travel in almost any kind of snow, and will go just about any place that can be reached by snowshoes. It is reputed to be capable of negotiating a grade of 50 per cent by the manufacturer; however, the Edison Company has not had occasion to work on anything over 45 per cent, which it ascends and descends very satisfactorily with a full load of two and one-half tons.

The power-end of this unit operates very much the same as a caterpillar tractor except that it only has one large, endless-type crawler-tread assembly that extends the entire width (56 inches) of the machine and runs completely around it. The open-type crawler prevents ice from building up between the treads and yet permits compaction of the snow between the treads by the bottom plate of the tractor, thereby developing the maximum traction obtainable from the snow. This crawler-assembly is made up of duraluminum-angle treads mounted on three link-belt endless chains, which, in turn, run in tracks attached to the frame of the tractor. There are snow-strippers attached to each tread that prevent snow and ice from building up on the body of the tractor and also on the treads themselves.

The engine, transmission-and-drive mechanism, along with the fuel-tank and radiator, are mounted on the bottom plate of the tractor and give it an extremely low center of gravity and excellent stability for side-hill travel.

The operator sits in a little cab mounted on the rear of the tractor-unit, in much the same position as the driver of an old-style horse-drawn cab. He is placed up in this little cab on top of the machine for visibility in rough terrain. The little cab and control-mechanism are attached to the body of the tractor by spandrel-arms extending around the crawler-assembly. The "Sno-Motor" pulls a sled which resembles a sea-sled in shape. The sled steers the unit in much the same manner that a rudder steers a boat. Most caterpillar tractors are guided by braking one crawler and driving on the other, but, obviously, that is not possible on the "Sno-Motor" since it only has one crawler. On each side of the sled there is a steel plate approximately four feet long and extending down into the snow about six inches, which is comparable to the rudder on a boat. The sled is connected to the rear of the tractor through a spandrel-pipe attached to a ball-and-socket joint. This permits independent movement of the sled, both horizontally and vertically, with respect to the tractor-end of the unit. A small winch or windlass driven by planetary gears from the engine is located on each side of the tractor. Steering is accomplished by taking up on one of the winch-cables attached to one of the front corners of the sled and slacking off on the other winch-cable, thus changing the angle between the motor and the sled. The operator can thus change his direction of travel in very much the same manner that a rudder changes the direction of travel of a boat.

The sled is approximately five feet wide and 18 feet long, resembling a flat-bottom boat or scow with both ends turned up. Two seats extend about half-way along each side from the front of the sled and will accommodate 12 passengers, since no provision is made for carrying either passengers or freight in the cab-and-tractor unit. The rear end of the sled is left free to carry equipment and supplies, or the entire sled may be loaded if no passengers are carried.

The "Sno-Motor" exerts a weight of only 170 pounds per square foot on the snow, or approximately the equivalent of an average man on snowshoes. It is capable of carrying a 2-1/2-ton load under practically any snow-condition. This performance is attributed to the single-crawler principle, which provides the greatest possible unbroken track-area and lessens the tendency to excavate into the softer snow-materials.

This machine will operate on bare ground, but it is not designed for such service and is more difficult to steer on such operation. On snow, the machine steers readily and turns on nearly as sharp a radius as most of the two-track tractors.

In the performance of this machine, a great deal depends on the operator and his ability to develop a sense of feel or touch for over-the-snow traction. A good operator can successfully take one of these machines almost anywhere that it is possible for a man on snowshoes to go, and with a capacity pay-load. There may be places such as steep slopes or ravines where extremely deep, powdery snow makes it necessary for the operator to buck out a trail. This is easily done by a series of short forward and backward runs until a compacted track or trail is established. However, once a track has been established, future travel over the route is both easy and quick.

Frozen side-hill travel is probable the most severe test for any type of equipment. This is successfully negotiated by the "Sno-Motor" by keeping it headed just enough up the hill to overcome the tendency to slip down, in very much the same manner that the dirt-track race-drivers skid their machines around sharp turns by keeping them pointed toward the inside fence.

The "Sno-Motor" is powered by a 95-horsepower, 6-cylinder Hercules gasoline engine with a special, double-float airplane-type carburetor suitable for operation in almost any position that the machine may be thrown into in a day's run. This engine also has a specially designed oil-pan and pump to insure lubrication at almost any angle. It has a 50-gallon gasoline tank, or enough fuel to last approximately 12 hours without refueling. Its speed ranges from a half mile an hour in low gear up to 20 miles an hour in high gear. The transmission has four speeds forward and one in reverse. The machine can travel backwards just as well as forwards. Snowshoes are always carried as auxiliary equipment for every passenger on all trips as a safety-precaution.

The Edison Company's "Sno-Motor" is one of five in use in the United States at the present time. The machine was designed and first built for use by the United States Forest Service at Mount Hood (Oregon). Other machines are in use at Sun Valley (Idaho), Yosemite Valley (California), and Estes Park (Colorado). At the present time the United States Army is investigating the possibilities of this machine for military service in remote snowbound regions.

The "Sno-Motor" fulfills a long-felt need for a safe and faster means of winter transportation in snowbound regions similar to the High Sierra country. In the first month the "Sno-Motor" traveled about four hundred miles back and forth from Huntington Lake over 10,000-foot Kaiser Pass to Florence Lake, and met every test of the road satisfactorily. It hauled men and supplies a distance of 30 miles in approximately eight hours over rugged mountain terrain that formerly required from two to four days of grueling, dangerous travel by snowshoes.

[Note: For illustration of the "Sno-Motor" see Trans. Amer. Geophys. Union, 1941, p. 971. Unfortunately the motion-picture promised for the Meeting failed to arrive.]

Southern California Edison Company, Ltd.,
Los Angeles, California

DETACHABLE LASHINGS FOR SKI-SAFETY

Walter J. Herz

The increasing number of accidents due primarily to the increasing number of snow mountaineers has caused the development of the National Ski-Patrol and tests for ski-proficiency.

The accidents are of two kinds: (a) Spiral fracture due to tight ski-lashings that in a spill cause the ski to have the power of a wrench on the leg; and (b) snowslides that under favorable conditions may become active menaces. Snow-surveyors have been the victims of both.

Detachable lashings are now under test but are criticized because they come loose too readily and cause emotional inconvenience or come off too late when the impact forces the leg through the crust with resulting fracture. Training and complete control are proposed by all as a compromise.

Through the assistance of Ranger H. I. Snider of the Tahoe National Forest a set of the Hjalmar "Hvam-Saf-Ski Toe-Irons" was obtained for exhibition purposes at the Meeting and will be put to further tests and report will be made at a future meeting. The Barieau "Solestrap and Toe-Iron" has also been generously loaned by its inventor, Jerome Barieau for test and report. Unfortunately the cancellation of the meeting at Salt Lake City, planned for June, 1942, will postpone this report until possibly the Regional Meeting at Corvallis, Oregon, in June, 1943.

BUSINESS MEETING

Fred H. Paget, Chairman, Executive Committee, presiding

REPORT OF CHAIRMAN OF EXECUTIVE COMMITTEE, WESTERN INTERSTATE SNOW-SURVEY CONFERENCE, TO PASADENA MEETING, JANUARY 16, 1941

First, I would like to review in general what has happened since our last Meeting at Sacramento in January, 1941.

Research Committee--At that Meeting your Chairman was authorized to appoint a Committee on Research. I did so, appointing as Chairman, Dr. Church, to be assisted by R. A. Work, Dr. Joseph Kittredge, Dean George D. Clyde, R. L. Parshall, and Merrill Bernard. I have asked Dr. Church to give you later on a short summary of what this Committee has done so far.

Changes in membership of Executive Committee--Your Executive Committee consists, as you know, of 20 members, five being elected from each of the four areas of the Conference. Since we last met two of these elected members have gone to the Army and following the procedure laid down in our By-Laws, two other men have been appointed to fill the vacancies. Both of these vacancies occurred in the North Pacific Area. George G. West of the United States Engineers at Portland and R. C. Farrow, Chief Hydraulic Engineer for British Columbia, were the members going into the service. Mr. West's place was filled by N. H. Leupold, also of the United States Engineers at Portland, and Mr. Farrow's place was filled by R. S. Frame, who is carrying on Mr. Farrow's provincial duties in British Columbia.

Niphometrology--Another advance during the year was the origination and acceptance (in some quarters) of a new word for snow-surveying and snow-surveyors. The word is compounded from two Greek words nipho meaning snow and metrology, the science of weights and measures. Snow-surveying thus becomes Niphometrology and a snow-surveyor becomes a Niphometrologist.

Reference to Committee--Two matters have been referred to the members of the Executive Committee for decision.

(I) What is our policy to be regarding the number of meetings held each year? On this, the majority decided on only one main meeting each year, the main one for 1942 to be held in Salt Lake City. This was to have been held there on June 15-20, in a combined meeting of the American Society for the Advancement of Science, the Section of Hydrology of the American Geophysical Union, and the Western Interstate Snow-Survey Conference. War conditions, however, have made it necessary to postpone this proposed meeting. Dean Clyde of the Utah State Agricultural College was designated Chairman for the program of the Conference.

The Committee also went on record as favoring Portland as the location for the main meeting of 1943. However, this will have to be ratified by the new Executive Committee which will be elected within the next few months.

(II) The other matter referred to the Committee was one instigated by Messrs. Lang and Jones. They were of the opinion that our Conference should change from a non-dues-paying organ-

ization to a dues-paying status, and asked that the membership be polled to determine its reaction. The majority of the Executive Committee agreed that the membership should be so polled.

Future organization--As you know, this Meeting brings to a close the term of office of your present Executive Committee which will give place to the new Committee just as soon as another election can be held. The first step towards this is the selection of one man for a Nominating Committee by the five members of each area. The term of office of the Chairman of the Board is limited to two years. The following suggestions, in my judgment, would tend to make the Chairman's duties less arduous:

(I) The appointment of a Publications Committee to handle the assembly, editing, and distribution of the Transactions.
(II) The appointment of a Membership Committee to keep our membership-lists current as far as possible and to eliminate duplicate mailings of Transactions.
(III) The appointment of a Solicitation Committee to solicit financial aid from organizations interested and benefiting from our work.
(IV) Appointment of a Treasurer to handle funds of the Conference.

Acknowledgment--In closing my "swan song", may I say that it has been a real pleasure to have acted as the Chairman of your Executive Committee during the past two years, and what small measure of progress has been made by your Committee is due to the support received from many members of the Conference, outstanding among whom has been Dr. Church.

Fred H. Paget, Chairman

REPORT OF TREASURER, WESTERN INTERSTATE SNOW-SURVEY CONFERENCE, TO PASADENA MEETING, JANUARY 16, 1942

One year ago when the accounting of the finances was put into my hands, we owed bills amounting to approximately $1,500.00. As of January 15, 1942, we owe approximately $600. We have, however, in the bank and accounts receivable--which should be paid within the next six months--a total of approximately $300, so that six weeks from now when this season's income and outgo come to an end, we probably will be behind some $300.

The indebtedness of $600 is in two accounts: Personal loan by Dr. Church, $400; American Geophysical Union, balance on cost of reprints, $200. As our $300 comes in during the next two weeks, $200 of this will be sent to Dr. Fleming to settle the American Geophysical Union printing bill in full. The remaining $100 will be paid to Dr. Church, reducing to $300 the loan he made to the Conference over a year ago.

An overall picture of our expenses and income during the last two years is as follows:

Expenses:			Income:		
Stanford Meeting, 1940	$ 425		From subscribers, 1940	$1000	
Seattle Meeting, 1940	1125	$1550	From subscribers, 1941	800	$1800
Sacramento Meeting, 1941	550	550	Advanced by Dr. Church	300	300
Totals		$2100			$2100

Fred H. Paget, Treasurer

CONTINUATION OF MEMBERSHIP OF EXECUTIVE COMMITTEE

Upon vote of the Conference the term of the Executive Committee of the Conference was continued until the end of the War as follows:

Area			
North Continental Divide	South Continental Divide	North Pacific	South Pacific
Lynn Crandall	J. Cecil Alter	G. H. Canfield	H. P. Boardman
H. T. Gisborne	George D. Clyde (Chairman)	Phil E. Church	James E. Jones
Walter E. Johnson	Ashton R. Codd	R. S. Frame	Joseph Kittredge
James C. Marr	R. L. Parshall	N. H. Leupold	W. A. Lang
O. W. Munson (Chairman)	Harry L. Potts	R. A. Work (Chairman)	Fred H. Paget (Chairman)

REGISTER OF ATTENDANCE AT PASADENA REGIONAL MEETING OF SECTION OF HYDROLOGY, AMERICAN GEOPHYSICAL UNION, AND WESTERN INTERSTATE SNOW-SURVEY CONFERENCE

[Letter S following name indicates person also took part in Snow-Survey Conference meeting on evening of January 16, 1942; many others, mostly students of the California Institute of Technology, came after the dinner to view the Swiss Avalanche Film and the Union Pacific Film of Sun Valley]

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Ashton R. Codd (S), U. S. Weather Bureau Office, Boeing Field, Seattle, Washington
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Arthur A. Young, Division of Irrigation, Pomona, California

ERRATA, TRANSACTIONS OF 1941

Part I-B, page 187: Figures 4 and 5 have the Figure numbers and titles interchanged.

Part I-B, page 190: Line 4, paragraph (c), should read "20 to 50 calories per square cm" instead of "20 to 50 calories per square inch."

Part III, page 979: In the next to the last paragraph, delete "Dr." preceding the name H. G. DORSEY, JR.

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Annual meeting	Year	Volume	No. pages	Price postpaid
1	1920*	None (mimeographed business meeting)	....	.....
2	1921*	Transactions (Bull. NRC, No. 17)	108	$1.50
3	1922*	None (mimeographed business meeting)	....	.....
4	1923*	Transactions (Bull. NRC, No. 41)	150	2.00
5	1924*	None (mimeographed business meeting)	....	.....
6	1925*	Transactions (Bull. NRC, No. 53)	80	1.00
7	1926*	Transactions (Bull. NRC, No. 56)	134	1.25
8	1927*	Transactions (Bull. NRC, No. 61)	297	3.00
9	1928*	Transactions (Bull. NRC, No. 68)	103	1.00
10-11	1929-30*	Transactions (all Sections)	314	1.50
12	1931*	Transactions (all Sections)	229	1.50
13	1932*	Transactions (all Sections)	401	2.00
14	1933*	Transactions (all Sections)	521	2.50
15	1934	Transactions Part I (all Sections except Hydrology)	258	1.25
	1934*	Transactions Part II (Hydrology)	376	1.50
16	1935	Transactions Part I (all Sections except Hydrology)	364	2.00
		Transactions Part II (Hydrology)	166	1.50
17	1936	Transactions Part I (all Sections except Hydrology)	260	1.50
	1936*	Transactions Part II (Hydrology and Regional Meetings Hydrology)	204	2.00
18	1937	Transactions Part I (all Sections except Hydrology)	264	1.75
	1937*	Transactions Part II (Hydrology and Regional Meetings Hydrology)	300	2.25
19	1938*	Transactions Part I (all Sections)	585	3.50
	1938*	Transactions Part II (Regional Meetings Hydrology)	180	1.25
20	1939	Transactions Parts I, II, III, IV (all Sections)	741	5.00
		Transactions Part I (Regional Meetings Hydrology)	140	1.25
		Transactions Part II (Symposium on floods)	94	1.00
		Transactions Part III (all Sections except Hydrology)	250	1.75
		Transactions Part IV (Hydrology)	257	1.75
21	1940	Transactions Part I (Stanford University Regional Meetings Hydrology)	144	1.25
		Transactions Part II (Washington Annual Meetings, all Sections)	643	3.75
		Transactions Part III (Richmond Symposium and Seattle Regional Meetings Hydrology)	280	1.75
		Transactions Part IV (Columbus symposia: Applications of mathematics in the earth-sciences and Hydrologic problems in the Ohio and Michigan basins)	84	1.00
22	1941	Transactions Part I (Sacramento Regional Meeting Hydrology)	216	1.50
		Transactions Part II (Washington Annual Meeting, all Sections except Hydrology)	368	2.50
		Transactions Part III (Washington Annual Meeting, Hydrology)	452	3.00
23	1942	Transactions Part I (Dallas and Pasadena Regional Meetings Hydrology)	171	1.25
		Transactions Part II (Washington Annual Meetings, all Sections)	(450)	4.50
Special	(1920)	A survey of research problems in geophysics (Reprint and Circular Series NRC, No. 11)	57	0.60
Special	(1937)*	Bibliography of Hydrology, United States of America: Years 1935 and 1936	78	0.30
	(1938)	Year 1937	68	0.30
	(1939)	Year 1938	78	0.30
	(1940)	Year 1939	86	0.50
	(1941)	Year 1940	90	0.85
Special	(1942)	Seventh General Assembly, International Association of Geodesy	64	1.00

An "*" following the year of publication indicates that the publication is out of print.

"NRC" is an abbreviation for National Research Council.

"All Sections" implies Transactions of General Assembly, and Sections of Geodesy, Seismology, Meteorology, Terrestrial Magnetism and Electricity, Oceanography, Volcanology, Hydrology (from 1931), and Tectonophysics (from 1940).

Orders, with checks payable to the "American Geophysical Union," should be addressed to the

General Secretary, American Geophysical Union,
5241 Broad Branch Road, Northwest,
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National Research Council

AMERICAN GEOPHYSICAL UNION

TRANSACTIONS OF 1942

PART II

TWENTY-THIRD ANNUAL MEETING
APRIL 3 AND 4, 1942
WASHINGTON, D. C.

REPORTS AND PAPERS

GENERAL ASSEMBLIES AND
SECTIONS OF GEODESY, SEISMOLOGY, METEOROLOGY,
TERRESTRIAL MAGNETISM AND ELECTRICITY,
OCEANOGRAPHY, VOLCANOLOGY, HYDROLOGY,
AND TECTONOPHYSICS

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INTRODUCTION

The American Geophysical Union was established in 1919 as the American Committee of the International Union of Geodesy and Geophysics, and its Executive Committee is the Committee on Geophysics of the National Research Council. The objects of the Union are to promote the study of problems concerned with the figure and physics of the Earth, to initiate and coordinate researches which depend upon international and national cooperation, and to provide for their scientific discussion and publication. In the accomplishment of these objects, the Union is divided into Sections following the plan of organization of the International Union of Geodesy and Geophysics. There are now eight Sections, namely, (a) Geodesy, (b) Seismology, (c) Meteorology, (d) Terrestrial Magnetism and Electricity, (e) Oceanography, (f) Volcanology, (g) Hydrology, and (h) Tectonophysics. A Section of Geophysical Chemistry was discontinued May 31, 1924, as the International Union had failed to provide such a Section. The Section of Hydrology was established November 15, 1930--matters pertaining to scientific hydrology referred to the American Geophysical Union had been previously looked after by special committees on Hydrology. The Section of Tectonophysics was established April 9, 1940, for the purpose of promoting and encouraging research of fundamental importance to our knowledge of Earth-structure not covered in any one of the other Sections of the Union.

Annual assemblies of the Union and annual meetings of its Sections for the discussion of reports and for symposia are held each year. The first 13 assemblies and meetings--those in each of the years from 1920 to 1932--were held in Washington, D. C. Besides the annual general assemblies and meetings of each of the Sections held since 1933 in Washington, D. C., regional meetings of the Section of Hydrology were held at Berkeley, California (1933 and 1934), at Pasadena, California (1936), at Denver, Colorado (1937), at Spokane, Washington (1937), at Davis, California (1938), at Los Angeles, California (1938), at Spokane, Washington (1938), at Stanford University, California (1940), at Seattle, Washington (1940), at Sacramento, California (1941), at Dallas, Texas (1941), and at Pasadena, California (1942). The transactions of annual assemblies and meetings through the ninth were published in the Bulletin series of the National Research Council as follows: Second, 1921, Bulletin No. 17; fourth, 1923, Bulletin No. 41; sixth, 1925, Bulletin No. 53; seventh, 1926, Bulletin No. 56; eighth, 1927, Bulletin No. 61; and ninth, 1928, Bulletin No. 68. Transactions of the tenth and eleventh annual meetings held in 1929 and 1930 were published in one volume in June 1930, and those of the twelfth, thirteenth, fourteenth, fifteenth, sixteenth, seventeenth, eighteenth, nineteenth, twentieth, twenty-first, and twenty-second annual meetings were published in June 1931, June 1932, June 1933, June 1934, August 1935, July 1936, July 1937, August 1938, July and August 1939, July and September 1940, and July and August 1941, respectively, in the series of miscellaneous publications of the National Research Council. The present volume, Part II of the Transactions of 1942, also one of the miscellaneous publications of the Council, includes the proceedings of the twenty-third annual meetings held at Washington, D. C., April 2 and 3, 1942. [The proceedings of the regional meeting of the Section of Hydrology held jointly with Section E of the American Association for the Advancement of Science at Dallas, Texas, December 30, 1941, including eight papers and reports, and jointly with the Western Interstate Snow-Survey Conference at Pasadena, California, January 16 and 17, 1942, including 13 papers and reports with discussions, are published as Part I of the Transactions of 1942.] At the first, third, and fifth annual meetings in 1920, 1922, and 1924, respectively, there were no scientific papers presented; therefore, the transactions for these were not printed but were mimeographed for limited distribution only.

The present volume (Part II) contains 104 papers and reports, with extensive discussions, presented at the twenty-third annual meetings of the Union and all of its Sections held at Washington, D. C., in 1942. As in the Transactions of 1941, the minutes of the General Assembly and of those of all of the Sections, with their appendices, have been included at the end of Part II. The total attendance of members and guests, despite the urgent demands upon all because of the War, was in excess of that registered, namely, 372. The attendance at the regional meetings was also excellent.

Three resolutions were adopted at the General Assembly. These related to (1) radio time-signal service maintained by the United States Naval Observatory and the Naval Communication Service, (2) need of provision, for the War and post-War needs, to insure continuity of hydrologic records, especially of precipitation, stream-flow, and ground-water supplies so essential to economic development, and (3) expression of appreciation to the authorities of the George Washington University for generous extension of the facilities of the University for the meetings.

There were two general assemblies of the Union. The first, held in the Hall of Government of the George Washington University, was devoted to the fourth award of the William Bowie Medal to NICHOLAS H. HECK, to an address by President W. C. LOWDERMILK, and to a lecture by

Director BRADFORD WASHBURN of the New England Museum of Natural History of Boston on "Recent explorations in the mountains and glaciers of Alaska." The second general assembly heard reports of officers and committees, discussed business matters and resolutions, and elected officers to fill vacancies.

At the meeting of the Section of Geodesy four papers related to geodetic surveys, three concerned improved techniques of observation and reduction, one reported on gravity-observations, and one discussed map reading and defense training.

The Section of Seismology heard four papers on seismic prospecting, periods and amplitudes of microseisms, determination of Earth's elastic constants, and progress-report on seismological activities.

There were ten communications before the Section of Meteorology, of which one is not published because of its bearing on problems of war. Four dealt with the wind, two with precipitation, two with general meteorological problems, and one with an apparent relation between radio-beam direction and certain meteorological conditions.

Of the twelve papers before the Section of Terrestrial Magnetism and Electricity, three related to atmospheric electricity, two told of general progress in geomagnetism, two concerned annual and secular variations, one considered magnetic bays, one gave an account of a geomagnetic survey of southeastern New York, one discussed the production of an isogonic chart, one dealt with the humidity-problem at a tropical magnetic observatory, and the twelfth discussed geomagnetism and the ionosphere.

There were eight papers and reports submitted to the Section of Oceanography including four progress-reports, three papers on results, and one giving an illustrated account of an expedition on the Askoy.

The Section of Volcanology held two sessions at which thirteen papers were presented.

Forty-three papers and reports of permanent research-committees were presented and discussed before three sessions of the Section of Hydrology; at a fourth session there was a round-table discussion bearing on these papers and reports.

The Section of Tectonophysics held a Symposium and Conference on "Mechanics of flow and crustal deformation," in which four papers were presented.

The General Secretary edited the manuscripts for publication after some preliminary editing by the secretaries of Sections. The cost of publication was met through allotment by the National Research Council and annual dues of members. As in past years, the Union is grateful for quarters provided without cost by the Carnegie Institution of Washington at its Department of Terrestrial Magnetism. Each of the authors, except for a few who could not be reached, revised a carbon of the master-copy from which the Transactions were printed by the offset method. The final master-copy was prepared by J. J. CAPELLO and W. E. SCOTT and was planographed by the Kirby Lithographic Company of Washington. W. C. HENDRIX redrew many drawings and, with J. W. GREEN, looked after the large amount of photographic work required.

Despite the world's troubled conditions the Union has continued effectively its purpose "to promote the study of problems concerned with the figure and physics of the Earth, to initiate and coordinate researches which depend upon international and national cooperation, and to provide for their scientific discussion and publication." In the past year the Union has taken steps to further increase coordination and collaboration, especially with the geophysicists of the whole Western Hemisphere, and to maintain that continuity of effort so necessary to progress in investigation of the earth-sciences.

J. A. FLEMING, General Secretary,
American Geophysical Union

AMERICAN GEOPHYSICAL UNION

TWENTY-THIRD ANNUAL MEETING

GENERAL ASSEMBLY

EVENING LECTURE SESSION

AWARD OF WILLIAM BOWIE MEDAL
PRESIDENTIAL ADDRESS
LECTURE

Washington, D. C.
April 3, 1942

FOURTH AWARD OF WILLIAM BOWIE MEDAL, PRESIDENTIAL ADDRESS, AND ILLUSTRATED LECTURE
APRIL 3, 1942

AWARD OF THE WILLIAM BOWIE MEDAL

CITATION

L. O. Colbert

Mr. President: I have been requested to present to you a distinguished member of the Union who has been chosen to receive the medal named in honor of WILLIAM BOWIE. The privilege is an honor to me because of our close association for a third of a century.

This medal was established by the friends and coworkers of WILLIAM BOWIE in recognition of his outstanding achievements in international geophysics and as one of the founders of the American Geophysical Union. It is awarded for distinguished attainment and outstanding contribution to the advancement of cooperative research in fundamental geophysics.

I am presenting one who has been active in the various geophysical fields of hydrography, oceanography, geomagnetism, and seismology. Considering his activities in retrospect I find an ever-present tendency to investigate and improve methods and equipment and to cooperate with others for the advancement of knowledge in each of these fields.

While serving as an officer on ships of the Coast and Geodetic Survey he was responsible for the development of the wire-drag. During the first World War he was transferred to the Navy and assigned to the Naval Experiment Station at New London, Connecticut. It was here that the practical application of the principle of transmission of sound waves in sea water was in experimentation for war purposes. Recognizing the application of this principle to hydrographic work, he actively promoted its use by the Coast and Geodetic Survey after the war. This method is now known as radio acoustic range-finding. It has been of outstanding value in hydrographic operations.

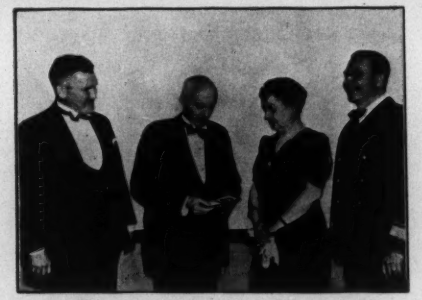
In 1921, on assignment in the Washington office of the Survey as Chief of the Division of Terrestrial Magnetism, he began that part of his career which in a large measure has qualified him to receive this Medal. He cooperated actively with the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. Through his efforts, the Cheltenham Observatory was established as the World Standard Observatory for magnetic measurements.

It was during this period that the Congress delegated to the Coast and Geodetic Survey the function of earthquake-investigations. His work in this field of geophysical research was responsible for a great stimulation in the study of seismology. His handling of the problem of cooperation of observations by many societies has brought well-earned honors to him. These have been accorded by the Seismological Society of America, the Jesuit Seismological Association, the Seismological Laboratory of the California Institute of Technology, and various universities.

He is an active member of many scientific societies. He has been President of the Philosophical Society of Washington, the Seismological Society of America, and the International Seismological Association of the International Union of Geodesy and Geophysics. We are all familiar with his creative work in the Union, culminating with the Presidency in 1935.

Mr. President, this candidate has had a most distinguished career in geophysics--he has brought outstanding contributions to its advancement. It is with much pleasure that I present to you NICHOLAS HUNTER HECK, author, magnetician, oceanographer, and seismologist.

President LOWDERMILK then presented the Medal with the following statement: Captain HECK, it is my privilege, on behalf of the members of the Union, to present you with this Medal because of your outstanding, unselfish cooperative research in geophysics and with the felicitations of your many friends and colleagues in all parts of the world.



FOURTH AWARD OF WILLIAM BOWIE MEDAL
TWENTY-THIRD ANNUAL MEETING, AMERICAN GEOPHYSICAL UNION
APRIL 3, 1942
(Reading left to right: Dr. W. C. Lowdermilk, President; Captain Nicholas H. Heck, Medalist; Mrs. William Bowie; Rear Admiral L. O. Colbert)

REPLY AND ACCEPTANCE

N. H. Heck

Admiral COLBERT: I am overwhelmed by the citation which I deeply appreciate.

Dr. LOWDERMILK: It is difficult to find words to express my appreciation of the great honor which you, on behalf of the American Geophysical Union, have conferred upon me. However, it is not on me alone, for no one can be worthy of this honor who does not have able associates at home and willing cooperators abroad and they are entitled to share in the honor. I am pleased to receive a Medal which bears the name of my long-time friend and associate, WILLIAM BOWIE, and to take part in a ceremony which commemorates the contributions of this great friend to geophysics. Since the Medal is presented in the midst of a great War, I prize it as a symbol of the purpose of the American Geophysical Union to encourage international work in geophysics, even though we do not know what the future will bring forth nor what is going to be the meaning of the word international.

PRESIDENTIAL ADDRESS

PROPHETIC SCIENCE

W. C. Lowdermilk

Less than three years ago, I was making a study of the lands of Mesopotamia where lie sepulchres of early civilizations. At the ruins of mighty Babylon, once the greatest center of power, learning, and culture in the ancient world, but now heaps without an inhabitant, we stood subdued as at a funeral and pondered the destiny of civilization. For in the valley of Mesopotamia eleven empires have risen and fallen in 7000 years. As we gazed upon the dusty ruins of one of the seven wonders of the ancient world--the Hanging Gardens of Babylon, where air-conditioning was in use 2600 years ago--the question kept coming up: Must nations rise only to fall? Is there no way for peoples to adjust themselves to land resources from century to century? Must our young nation of the United States of America also rise only to fall? Our present peril emphasizes this question. For the ruins of Mesopotamia tell of human sacrifices to the failure of peoples of the past to find a lasting adjustment to Earth's resources.

Why did great nations of former times decline and fall? Archaeologists have dug out of buried ruins the evidence that peoples of the past achieved an agriculture to support dense populations, as well as skills in crafts, organization in Government, beginnings in science and refinements in living, which amaze us even in this day of wonders. The population of Mesopotamia is probably only a tenth of that of its most prosperous period; and modern buildings are no counterpart of those now in ruins. Why should this be? What has happened to bring about such colossal tragedies in the long course of civilization? We can not believe it was adverse change of climate as some have suspected. For whatever the changes in climate, they were not severe enough in arid Mesopotamia to cause the downfall of prosperous nations founded on irrigation-farming. The land is still in place and the great twin rivers of the Tigris and Euphrates still flow through the land ready to be spread upon the fields as in ancient times. The land may be made to produce with the measures of old, as much as it ever did, when certain areas of saline accumulation are drained. Moreover, conservancy-works built with powered machinery and of reinforced concrete will irrigate today more land than was ever cultivated before at any one time and will support a greater population than ever lived in this ancient "Garden of Eden." Nor again, was the downfall of nations in Mesopotamia due to land-wastage by erosion such as so severely damaged other parts of the Old World. For these are flat alluvial lands with little rain where soil-erosion is not enough to note. The soils have remained in place through thousands of years and only need life-giving waters to yield bountiful crops.

Whatever their internal weaknesses, however, the nations of Mesopotamia were most frequently crushed by invasions of peoples out of surrounding grasslands. Hardy denizens of the steppe and desert, disciplined by hunger and hardship, looked upon and coveted the abundance and comfort of prosperous villages and teeming cities of irrigated plains. From time to time they swept out of the grasslands and hills and robbed and sacked and destroyed and passed on; or they infiltrated into outlying villages and cities. At times they replaced the former population and became farmers only to be swept out by a later invasion of denizens from the grasslands or by invasions of rival powers. From time to time the cradle of mankind was left in ruins or waste to proclaim one failure after another of mankind to adjust itself to mother Earth.

At our Annual Meeting last year, Dr. R. M. FIELD, in his Presidential Address to the Union, analyzed this problem with profound insight. Uneven distribution of the Earth's resources, uneven development of branches of the human race and uneven development of the arts and sciences set the stage for exploitation of others and of the Earth by persons and nations in positions of advantage of place or in time. When peoples suffer privations or fear of privations of primary needs, they follow their leaders into war for self-preservation. When peoples fear or suffer loss of their rights, they will also defend themselves even to the extremity of devastating war--all of which tells of the inflexibility of peoples because of their ignorance of what Dr. FIELD calls Geoscience. In other words, uneven advance of knowledge and use of Earth's resources with exploitation has from time to time given rise to war, with both its destruction and stimulation to new adjustments.

And now again, after 7000 years of civilization, war has blighted the world of our day, but with an important addition. The Old World was made desolate by wars served with the simplest sort of implements. The sword and spear, catapult and battering-ram, the horse and camel, wind and fire, were all that warriors of the ancient world had at their disposal for the destruction and decimation of armies and populations. Social structure was likewise simpler with little division of labor, and there were no large-scale industries hungry for fuels and raw materials. But war today is served as never before with marvelous advances of science, in guns of long range and high accuracy, in power-driven machines, in chemistry of high explosives, in powered transportation in the air, on the land and sea and under the sea, and with fuels and raw materials from every corner of the Earth. Never before has it been possible to assign so much of a Nation's manpower to the making and use of munitions of war, as powered industry makes possible today. And now the works and achievements of mankind and human populations, military and civilian, are being destroyed and annihilated as never before in the history of the human race. What then, is to be the destiny of civilization when nearly every discovery of science is used indirectly or directly to magnify the powers of destruction and annihilation--when science becomes a hireling of the Gods of War?

Science serves war more than peace. When aggressor nations carry out well and long-planned research and make use of the greatest advances in the sciences to surprise and overwhelm peoples selected for their victims, we must in turn make use of every means at our disposal to protect our people and to defeat such an enemy. We must do all that is necessary to safeguard our liberty of action to develop here in the New World the American Dream. For here is the last stand of the westward trek of civilization from its beginnings in the ancient world. "This is the place", for a new civilization, founded upon conservation and cooperation.

Our Government has enlisted scientific forces on a national basis chiefly in emergencies of war. It was during the Civil War in 1863 that President LINCOLN established the National Academy of Sciences; it was in 1916 in World War I that President WILSON established the National Research Council and the National Advisory Committee on Aeronautics to advise the armed forces of our country; and in 1940 in this World War, President ROOSEVELT established the National Defense Research Committee for the physical sciences and soon after, similar committees for biological and medical sciences and later formed an overall coordinating body--the Office of Scientific Research and Development of which Dr. VANNEVAR BUSH is Director.

All these agencies are war babies. The more recent arrivals have additional authority to take the initiative in solving problems and to farm out such problems for solution to going and staffed scientific institutions of the country. So heavily does modern warfare lean on science today that this arm of National Defense is likely to be enlarged to greater scope and effort in the future. It has been said that warfare is the business of the soldier, sailor and pilot, but today it is no less a war of the physicist, of the chemist, of the farmer and the miner, of the metallurgist and the machinist. We find it necessary to enlist in our modern warfare, scientific forces on a national scale to equip and supply our fighting forces to defeat a foe that makes full use of science against us.

While certain nations were preparing for attack, our Government gave too little support to science in the interests of National Defense. And if it were not for the independent work of endowed research-institutions and State universities, our armed forces would be at a far greater disadvantage than they are today. Our country owes a debt that it can hardly repay for bodies of information built up with painstaking research, and for instrumentation and skills developed in highly trained personnel of these institutions. Now we have the scientific forces of the country highly marshalled for the supreme effort in this war with the aggressor nations.

After victory, for we must have victory if it takes a generation, will we also demobilize our science as we demobilize our army? Will we discharge our war scientific agencies with speeches and medals? Do we need science chiefly to serve us in times of war? Do problems of peace also require a full marshalling of our scientific agencies? Today we devoutly commemorate the Crucifixion of the Prince of Peace. This profound tragedy makes us see how humanity today is making the most colossal human sacrifice of all time to its failure after 7000 years of civilization to find a lasting adjustment to resources of the Earth. This war is overwhelming evidence of our failure and together with the failure of other nations of the world during so-called peace, to work out in cooperation solutions to this age-old problem. As division of labor within our social structure becomes more complex with more and more large-scale industries, it takes more than food to feed our civilization today; it also takes fuels and many kinds of metals, and other raw mater-

ials that come from far corners of the Earth. Advances in the science of using such materials of the Earth have given more and more ground for conflict between nations, as well as ways for co-operation. But political theory and practice have not kept up with this progress of science. Rather than contributing to solutions to the age-old problem, science has aggravated it under present status of national and international politics. In recent times the sacrifices to these failures have become greater and greater, and suffering humanity of the Earth cries out; how then, shall we be saved? How shall mankind be saved from destruction by the engines of science?

Ways of salvation have been handed down by prophets of the spirit 3000-2000 years ago and recently in another way in the Atlantic Charter of Four Freedoms. What then, is lacking? Hitherto a way of salvation by prophets of the earth-sciences has not yet been fully proclaimed. For the spirit of civilization lives in the flesh so to speak, of natural resources of the Earth used and organized for human needs. Ignorance of the nature of the materials and forces of his earthly home has denied mankind reality to his spiritual hopes. But now as we acquire more and more knowledge of the Earth, of the materials and of the forces out of which we may build a lasting civilization, mankind is entering a new era of unsurpassed possibilities. As neolithic man passed from the stage of food-gatherer to that of food-producer, we must advance out of the stage of the exploiter--the waster--to that of the conserver, to use materials with renewal. If civilization is to endure for 7000 years into the future, whatever its spiritual guide, it must be founded on conservation of the Earth's resources.

As history is the integration of biological sciences, geophysics is an integration of the physical sciences. Here is a way out; but a solution to the age-old problem of civilization of finding an adjustment to its earthly home does not lie in any one specialized field of earth-science. For knowledge of the Earth is arbitrarily divided into compartments because of limitations of the human mind. And the basis for our solution so long sought for, is found in the totality of earth-science--as an integration of the several branches of geophysics, in the broad scope of these sciences.

It is for this integration of geophysical sciences that our Union was established in 1919 after World War I. The American Geophysical Union is, therefore, more a child of peace than of war; it is a hope of construction and conservation, rather than of destruction and waste. The content of the disciplines of the American Geophysical Union is the same that is required for the solution of this problem of the ages. For the problems of peace transcend and include the problems of war. We have in our hands one of the great instrumentalities for bringing in a new age of creative endeavor.

After victory, rather than demobilize the scientific agencies of the nation mobilized for war, we should keep them fully marshalled, but directed toward the greater problems of a constructive and creative peace. For peace, like democracy, can not remain static--it must be creative; otherwise it is nothing more than an armistice. The problems of peace are, as we see by a survey of the wrecks of time, greater and more difficult and complex than the problems of war. We need not less, but more science for peace. Science that has too often in the past been a hireling of exploitation and greed, may also serve conservation and cooperation. This world-wide war may be made to mark the end of an era of exploitation of humanity and of the Earth and the beginning of a new era of conservation and cooperation. The forces that will create a new era must be founded on knowledge and on understanding of the earthly home of civilization, to implement and support the spiritual goals of cooperation.

For 7000 years of civilization, mankind has failed to find a lasting solution to this problem of survival. It is only within the last two centuries that science of the Earth has disclosed, as through a glass darkly, the nature of the materials, forces, and processes that furnish the physical basis for civilization. It is within the scope of the Sections of Geodesy, of Seismology, of Terrestrial Magnetism and Electricity, of Oceanography, of Volcanology, of Hydrology, and of Tectonophysics that such information and techniques are developed. It is through the integration of the fields of these Sections that we may make a comprehensive attack upon this vital problem of the ages, and serve not only the present but the future.

By measuring forces at work in the Earth with the techniques of these fields, we determine trends of processes as affecting or as modified by human occupation of the Earth. Science in this way becomes a prophetic element in civilization. It gives us a new hope of solving this 7000-year old problem. With the instruments of the earth-sciences, we take a back-sight over 7000 years of more or less failures and turn our transit to take foresights to survey the course of civilization for a thousand years or more that may be traveled by Heaven-inspired, hope-impelled, and earth-bound mankind.

LECTURE

RECENT EXPLORATIONS IN THE MOUNTAINS AND GLACIERS OF ALASKA

Bradford Washburn

(Abstract)

This public lecture, illustrated with colored motion-pictures of the beauty-spots of the country traversed, gave an account of the author's exploration of the Mount Hayes Region in Alaska, under the sponsorship of the New England Museum of Natural History, Boston. The Expedition of the summer of 1941 was not only a contribution to the geographical knowledge of Alaska, at a time when such knowledge was becoming of crucial value to the United States, but was also a successful demonstration of the value of airplanes for such work. Not only were planes used in reconnaissance and photographic flights over the whole region but all supplies were parachuted to the party, which kept in constant touch with the main base by two-way radio. Work that would have required three months by former methods was finished in three weeks. A thousand square miles were covered by aerial photographs. These included some areas that were practically unknown and hitherto entirely unmapped because of their inaccessibility. Despite the use of leased planes the cost of the Expedition was but one-third of that which would have been required by older methods.

Following the lecture, the Lecturer, Medalist, and President held a reception to the Members of the Union and Guests.

AMERICAN GEOPHYSICAL UNION

TWENTY-THIRD ANNUAL MEETING

SECTION OF GEODESY

REPORTS AND PAPERS

Washington, D. C.
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INVESTIGATION OF THE EFFECT OF HEAVY CONSTRUCTION ON NEARBY BENCH-MARKS

Howard S. Rappleye

The investigation under discussion has resulted from a growing conviction on the part of some of us in the Section of Leveling of the Coast and Geodetic Survey that, in many cases at least, poor checks obtained in repeat leveling, when starting or tieing out new lines of levels, result from lack of stability of the bench-marks instead of "sloppy leveling" as is often assumed.

It seems only natural to be skeptical of the stability of a bench-mark in the top of a concrete post extending 3-1/2 or 4 feet into the ground and to believe that a bench-mark in the foundation of a large building or a heavy bridge-abutment will maintain its original elevation. However, we have gradually been forced to the conclusion that not all is stable that looks that way and in order to test, under controlled conditions as far as possible, the possibility that massive structures can undergo changes in elevation, we started wishing for a big construction job, conveniently located on which we could experiment. About that time the new War Department Building across the Potomac River was proposed and we began scheming to make this gigantic building produce a by-product of possible interest to the surveying profession.

As you probably already know, the building now under construction is a reinforced-concrete structure having a ground plan resembling a pentagonal doughnut. The general outline of the ground-plan of the building is a regular pentagon about 926 feet on a side and the interior court is also a regular pentagon with sides 360 feet in length. The whole structure is supported on upwards of 40,000 concrete piles. The load-bearing characteristics of the ground under the building vary from good to bad and possibly, on one edge, to very bad, since the building extends out over the edge of the landing field at the old airport.

The plan for the proposed investigation which was placed before the Constructing Quartermaster's Office through W. N. BROWN provided for the establishment of a total of 25 bench-marks in the walls of the building. It was planned to put four in each of the five exterior faces and one in each of the interior faces. This would mean that around the outside of the building the marks would be approximately 230 feet apart and that in the court they would be approximately 350 feet apart. These marks would be established rapidly as the walls reached the necessary height above the grade of the finished ground-surface around the building and it was proposed to level over them at frequent intervals during the remainder of the period of construction and for a considerable time after the building had been finished.

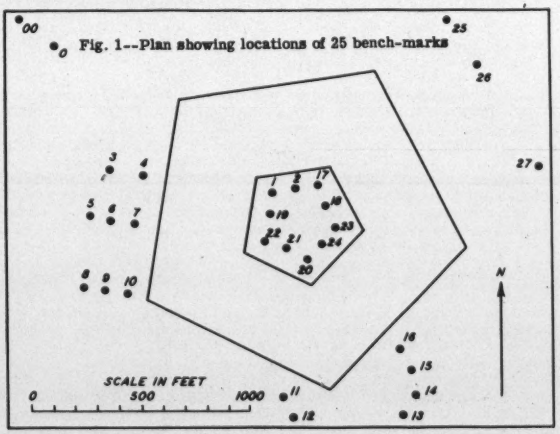

Fig. 1--Plan showing locations of 25 bench-marks

When our plan came to the attention of FREDERICK H. FOWLER and Professor LEONARD C. URQUHART, consulting engineers in the office of the Constructing Quartermaster, these gentlemen seemed to think well of the idea but also suggested that, if we were going to the trouble of doing so much field-work, it would be well to attempt to "kill two birds with one stone" and also investigate the behavior of the ground-surface around the building and in the court during the driving of the more than 40,000 piles required for the foundations of the building. Accordingly, after several conferences with the architects and engineers in actual charge of the construction in the field, it was decided to construct approximately 25 ground-marks scattered in groups around the building and to include these marks in the program of leveling. The establishment of the marks was done by the engineers in charge of construction and the leveling has been done by personnel from the Section of Leveling, Coast and Geodetic Survey.

The first leveling was undertaken October 15 to 17, 1941, and in addition to touching upon all of the ground-marks then in place, the leveling was carried to a pair of marks in Arlington Cantonment established as local or working control for this project. The leveling was also carried to several bench-marks at considerable distances from the construction activities to tie the whole system to the first-order control net and to guard against possible accident to the local control-marks in the Cantonment.

Owing to the fact that stone-facing is being used on the exterior walls of the new building, the establishment of the marks in the building itself has had to wait until the bottom courses of the stone-facing are placed. Only the four marks in the exterior face of the "B"-section have been set and leveled over to date.

Up to the present time nine levelings have been made over all marks accessible at the time of each leveling and the work is still going on. Not all of the original ground-marks are still in existence. A gigantic storm-sewer trench destroyed one. Grading operations recently destroyed three more. Adverse conditions of weather and a low spot put another one in the middle of a young lake for the winter, though we hope to recover that one later on. The face of the landscape changes so rapidly that even from week to week it is not always possible to touch upon the marks in the same order nor is it always possible to follow the same route from one group to another. Pile-driving equipment, tractors, trucks, bulldozers, steam-shovels, and all manner of rumbling, rattling, and jarring equipment continually hamper the field-work and make the site a nightmare for anyone trying to nurse a sensitive bubble to the center of its tube and to hold it there long enough to read a rod. However, in spite of the adverse working conditions, and the fact that it requires from 1-1/2 miles to 1-3/4 miles of leveling to run from the local control-marks over the other marks in the various groups and back to the local control-marks for a check, we feel that we have done some really good leveling and that we are gradually accumulating really useful data.

The time-limit on this paper will not permit of a bench-mark-by-bench-mark description of our findings, but, for the purpose of this preliminary or progress-report, the results can be reported for the various groups of marks and will, I believe, be of interest.

The two marks established for the local control were set well away from the construction in the Arlington Cantonment reservation and were designated "0" and "00". One of these was in the retaining wall around the corner of the swimming-pool where it extends into the toe of a rather high steep bank. The other is about 100 yards away and in the abutment of a small bridge carrying one of the Cantonment roads over a small creek. Each new leveling is started from these marks and is checked back on them for a closure. Each new leveling is computed with relation to the first leveling over the marks and the differences are determined in the sense new elevation minus old elevation. This means that if a plus difference is developed, upward movement of the mark relative to its original elevation is indicated and, of course, a minus difference indicates a settlement of the mark with relation to its original elevation.

The marks on the "B"-side (Nos. 3 to 10, inclusive) showed a tendency to settle slightly until November, when they were down by amounts varying from 2.5 mm to 4.3 mm. From then until the middle of February there seems to have been a tendency for the marks to recover. By the middle of February four of the marks exhibited plus differences and four of them minus differences, but all of the differences at that time were within the range from -1.1 to +0.9 mm. On March 11 the differences were all minus but ranged from -1.5 to -0.2 mm.

In the group of two marks on the "A"-side only one has remained accessible throughout the work to date, a lake having developed around the other. The one mark, No. 11, settled quite continuously until about Christmas, when it was down 6.3 mm, but recovered to -2.5 mm in January

and in March the difference was -2.7 mm.

The group of four marks on the "E"-side settled rather rapidly to the middle of November by amounts varying from 3 to 5 mm and then slightly recovered until in February the three remaining ones were within the range from 0.0 to -1.0 mm. In March two of these three were +0.4 and -0.1 mm away from their original elevations and the third was up 2.4 mm, though in all honesty it should be pointed out that at that time a steam-shovel had worked all around that mark and left it in the top of an earth-tower about 10 or 12 feet high. All marks in the group on the "E"-side have now been destroyed by grading operations.

The group of marks, ten in number, in the court have undergone rather rough treatment during construction activities and some of them are not now recoverable, though sometimes we recover one that has been buried under a pile of lumber for a month and sometimes another one that has been buried and then resurrected. This group has remained quite stable during the period from October, 1941, to March, 1942. The greatest minus difference observed on any of these marks was -2.7 mm and the greatest plus difference was +3.0 mm.

The three marks on the "D"-side of the building, out on the edge of the old airport, have misbehaved very satisfactorily. These marks were first touched upon late in October and by the middle of November were down from 0.7 to 2.4 mm. From then on they kept going down until in February they were down by 46.6, 16.3, and 55.7 mm, respectively.

The four marks in the wall of the "B"-side of the building were first touched upon in February and about one month later all showed signs of settlement ranging from 0.9 mm to 3.9 mm.

Since the work is still going on and has not yet passed through a complete cycle from warm to cold and back again to warm weather, we certainly are not justified in attempting to draw any definite conclusion.

However, one very interesting bit of information was developed in connection with our local control-marks. You will remember that bench-mark "0" was located in the corner of the retaining wall around the swimming-pool and that bench-mark "00" is in the bridge-abutment. The various leveling developed differences as follows: -0.4, +0.2, -0.5, +0.4, +1.8, +4.3, +0.1, and +0.5, the signs being taken to represent movement of "0" relative to "00". The +1.8-mm difference occurred on January 8 and the +4.3-mm difference on January 14. You will doubtless recall that we had a severe cold spell during that period. It is quite evident that the corner of the swimming-pool and the retaining wall around it heaved during the cold snap and then settled back again after the severe freezing weather was over.

Now suppose that someone had attempted to start a new line of levels from those two marks during that cold snap. The levelman would have failed to get a check and would have had to go on to other marks. He would probably have arrived at the conclusion that the original leveling over these two marks was at fault since to all outward appearances they were both established in structures which would not be disturbed by a short period of freezing weather with relatively shallow frost-penetration such as occurs in these latitudes. On the other hand, another levelman working a week or so earlier or possibly a week or two later would have secured a beautiful check between these two marks and would have been thoroughly convinced that both he and the levelman who preceded him were doing good work.

Now some of you, if you choose to discuss this paper at all, will, in all probability, point out the fact that a large number of the differences in elevation reported are so small as to be well within the probable inaccuracies of the leveling and the sad part is that it is true. However, you must realize that special and unusual care and patience have been used in carrying on this leveling and that we have a total of nine levelings to date. These facts do, I believe, warrant us in considering smaller than usual differences as real and not the result of errors in leveling. And yet the fact remains that at least a part of the reported movements are undoubtedly due to uncertainties in the leveling itself.

If conditions resulting from the present emergency do not interrupt this investigation, I believe that, as time goes on, we will be able to assemble a considerable amount of really interesting and useful information concerning the behavior of this particular building and the ground around it. While we are perfectly willing to admit that the results of this particular investigation will not settle all questions as to the stability of bench-marks nor will we be able to lay down any general rules or laws for the treatment of discrepancies developed by repeat leveling, yet we hope to be able to show the need for and advisability of further investigation and we should be able to perhaps

indicate the directions in which such further investigation should be pushed.

U. S. Coast and Geodetic Survey,
Washington, D. C.

USE OF ACCOUNTING MACHINES FOR MASS-TRANSFORMATION FROM GEOGRAPHIC TO MILITARY-GRID COORDINATES

Frank L. Culley

The use of accounting machines for computing military-grid coordinates is not the result of any new mathematical or mechanical discovery. It is merely the adaptation of an available means of rapid computation of known formulas. In other words, applying the assembly-line method for converting data from one form to another.

With hundreds of thousands of points for which geographic positions were known and for which rectangular coordinates were desired, the conversion from the one to the other in a short time could not be made without a tremendously large organization of computers and a large number of machines; and computers were becoming scarce.

Less than one year ago the idea was conceived of using accounting machines for making these computations. The usual impediments of professional jealousy and prejudice to new ideas had to be overcome. Consequently a demonstration was arranged in New York City. The demonstration proved to those who sponsored the idea that it was practical and to those opposed to the idea that it could be done, but they did not believe it. After careful study by Dr. BLANCH and Mr. PFEFERMAN of the Mathematical Tables Project of the Work Projects Administration in New York City, the procedure was worked out and the order for equipment placed.

Meanwhile the Military Grid Project which was a part of the United States Coast and Geodetic Survey Project of Work Projects Administration in New York City proceeded to assemble the geographic positions which were to be converted to grid-coordinates.

In order to keep track of the data and to easily identify the individual stations, a serial number was assigned each station as follows: The data were divided into bundles of less than 1,000 stations each. The first three figures of the serial number identified the bundle and the last three identified the station in that bundle; for example, 005-936 indicates station No. 936 in bundle No. 5. These numbers were used in place of the names which in cases of duplicate names would cause confusion.

Only the general procedure will be outlined and no attempt will be made to show every step in the computation of these coordinates. The example used is the conversion of a point for which the latitude is 36° 44′ 02.″523 and the longitude is 76° 35′ 54.″220 to military-grid coordinates.

The conversion from geographic positions to grid-coordinates consists of interpolation from the five-minute tables given in United States Coast and Geodetic Survey's Special Publication No. 59. The formula used is a simplified form of the one given in Special Publication No. 59, adapted for five-minute intersections instead of one-minute intersections. This formula is

$$X = A_1 X_1 + A_2 X_2 + A_3 X_3 + A_4 X_4$$

and

$$Y = A_1 Y_1 + A_2 Y_2 + A_3 Y_3 + A_4 Y_4 - A_5 (\Delta^2/2)$$

The term $[- A_5 (\Delta^2/2)]$ is the extra term necessary for use with five-minute intersections. $A_1 = C_L (1 - C_P)$; $A_2 = C_L C_P$; $A_3 = C_P (1 - C_L)$; $A_4 = (1 - C_P) (1 - C_L)$; $A_5 = C_L (1 - C_L)$; Δ^2 = second difference for values of Y at intervals of one degree of latitude along the central meridian of a zone.

Considering five minutes of latitude, or five minutes of longitude as unit-distance, C_P = fractional distance the station is north of the southern boundary of its five-minute quadrangle, C_L = fractional distance the station is west of the eastern boundary of that quadrangle (see Fig. 1).

The first step in the process was posting the tables in Special Publication No. 59. One master-card (No. X) was punched with the latitude and longitude of the southeast corner and the

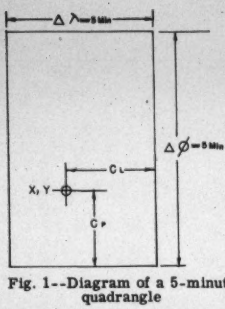

Fig. 1--Diagram of a 5-minute quadrangle

X- and Y-values of all four corners for each five-minute quadrangle in one zone. However, only the (X_4 Y_4)-values were punched directly from the tables. The values were then difference tested to detect any mistakes in punching. Over 400 mistakes were discovered in the printed tables by this test.

Master-cards X for five-minute quadrangles were sorted into latitude-groups and these groups were arranged in ascending order of latitude. Each latitude-group was then sorted in descending order of longitudes. Then the value of X_4 Y_4 for one quadrangle is common to the value of X_1 Y_1 for the quadrangle just east of it. The reproducer was then set up to punch the (X_4 Y_4)-values which are on this card in the (X_1 Y_1)-columns of the following card. The cards were then rearranged so that (X_4 Y_4) and (X_1 Y_1) for one quadrangle were transferred to the columns on the following card as (X_3 Y_3) and (X_2 Y_2), respectively, for the next quadrangle south of it. The transfer of the (X_4 Y_4)- and the (X_1 Y_1)-values to the (X_3 Y_3)- and (X_2 Y_2)-columns of the next card was done in one operation (see Fig. 3).

On another set of master-cards X, the value of one-half of the second differences for values of Y for the corresponding degrees of latitude were punched (see Fig. 5). The tables are now posted and Special Publication No. 59 need not be referred to again.

From the geographic-position data the serial number and position are punched on card 1 by one key-punch operator. This operation is duplicated by another person on card 2. The cards are then run through the collator and compared. When an error occurs the machine stops and the cards in question are pulled out. The position and serial number are then gang-punched from card 1 or card 2 onto cards 3 to 8 and onto master-cards OX and O (see Figs. 6 to 15).

The machine is then wired for use of card OX so that the difference in minutes and the next lower number divisible by five is obtained by punching 0 in column (10) if 0, or 5, has been punched in column (4), punching 1 in column (10) if 1, or 6, has been punched in column (4), etc. The value in column (10) is multiplied by 60, the product added to columns (5) to (9), and the result punched in columns (45) to (50). This result is divided by 300 to obtain C_L which is punched in columns (21) to (26). C_P in columns (33) to (38) is obtained from the latitude in a similar manner (see Fig. 6). Now A_1, A_2, A_3, A_4, and A_5 are computed from various combinations of C_P and C_L. Whenever possible a test is made after each operation to detect any mistakes. For example, after computing A_1 and A_2, we have $A_1 = C_L (1 - C_P) = (C_L - C_L C_P)$ and $A_2 = C_L C_P$. So $(A_1 + A_2) = C_L$ for each card; and therefore, $\Sigma A_1 + \Sigma A_2 = \Sigma C_L$ for any group of cards.

A summary test is then run on as many as 3,000 cards at one time. If the sum of all A_1's and and A_2's on these cards equals the sum of the C_L's, then A_1 and A_2 should be correct on each card. If these sums are not equal, a balancing test is made on each card by adding the A_1 and A_2 to see if it equals C_L. If there is a card on which $(A_1 + A_2)$ does not equal C_L the machine stops and the operator removes the card which contains the error. The summary tests and the balancing tests are made at the rate of 150 cards per minute. Another test is that for each station $A_1 + A_2 + A_3 + A_4 = 1.00000000$.

All of the cards are sorted now so that the master-card X for each five-minute quadrangle is followed by all the cards for stations within that quadrangle. The (X_1 Y_1)-values are punched from card X on card 1, (X_2 Y_2) on card 2, (X_3 Y_3) on card 3, (X_4 Y_4) on card 4, and half the second difference for Y on card 5. Also A_1 is transferred from card OX to card 1, A_2 to card 2, A_3 to card 3, etc. The cards are then stacked in the multiplying machines and the products A_1 X_1 and A_1 Y_1 are computed and punched on card 1, A_2 X_2 and A_2 Y_2 on card 2, A_3 X_3 and A_3 Y_3 on card 3, A_4 X_4 and A_4 Y_4 on card 4, and $-A_5$ ($\Delta^2/2$) on card 5.

These values are added from the five cards for each station and the resulting values of X- and Y-coordinates are punched on the summary card (No. 6).

The formula for computing the gisement (the angle between true north and military-grid north) is

$$\text{Gisement} = t \sin \phi - \frac{1}{24} t^3 \left(\frac{\pi}{180 \times 60}\right)^2 (\sin \phi + \sin 3\phi)$$

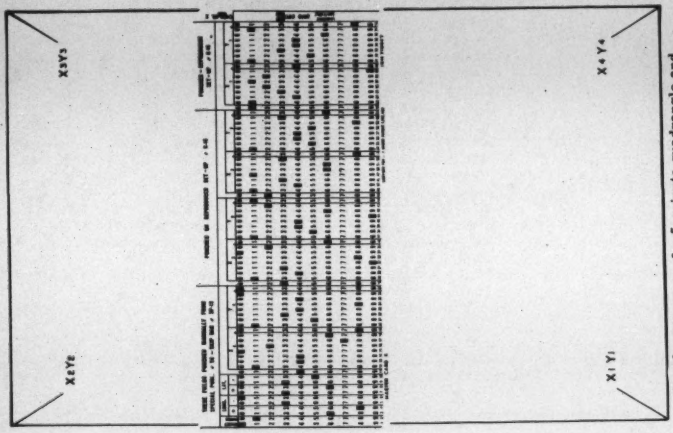

Fig. 2--Diagram of a 5-minute quadrangle and its master-card on which are punched X- and Y-values for four corners and geographic position of southeast corner

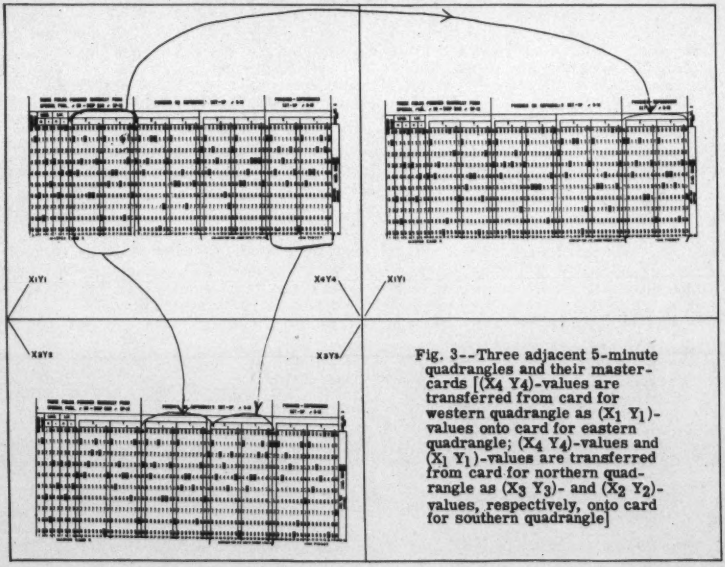

Fig. 3--Three adjacent 5-minute quadrangles and their master-cards [$(X_4\ Y_4)$-values are transferred from card for western quadrangle as $(X_1\ Y_1)$-values onto card for eastern quadrangle; $(X_4\ Y_4)$-values and $(X_1\ Y_1)$-values are transferred from card for northern quadrangle as $(X_3\ Y_3)$- and $(X_2\ Y_2)$-values, respectively, onto card for southern quadrangle]

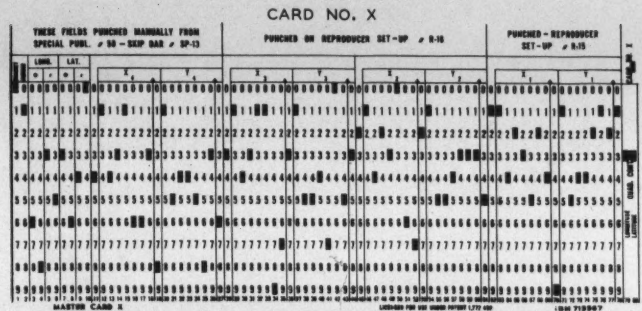
CARD NO. X
THESE FIELDS PUNCHED MANUALLY FROM SPECIAL PUNCH. ⌀ 58 – SKIP BAR ⌀ SP-13
PUNCHED ON REPRODUCER SET-UP ⌀ R-16
PUNCHED – REPRODUCER SET-UP ⌀ R-15
LONG.
LAT.
MASTER CARD X
LOCHARD PUNCH AND CARD PATENT 1,772,482
IBM 719367

Fig. 4--Master-card for example illustrated showing X- and Y-values of four corners; bracket number indicates relation to central meridian (This card is used in all zones for quadrangle in same latitude and same distance and direction from central meridian)

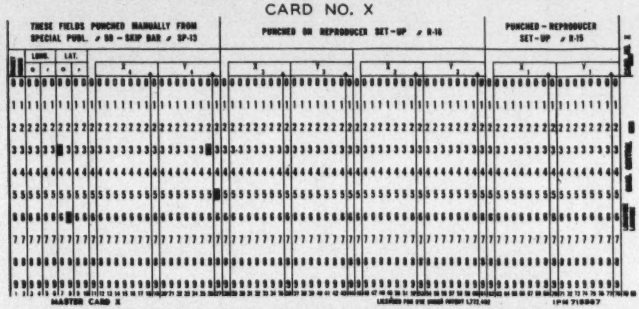
CARD NO. X
THESE FIELDS PUNCHED MANUALLY FROM SPECIAL PUNCH. ⌀ 58 – SKIP BAR ⌀ SP-13
PUNCHED ON REPRODUCER SET-UP ⌀ R-16
PUNCHED – REPRODUCER SET-UP ⌀ R-15
LONG.
LAT.
MASTER CARD X
LOCHARD PUNCH AND CARD PATENT 1,772,482
IBM 719367

Fig. 5--Second master-card used for computing fifth term in formula for Y-value (Half the second difference of Y-value is punched against degree of latitude)

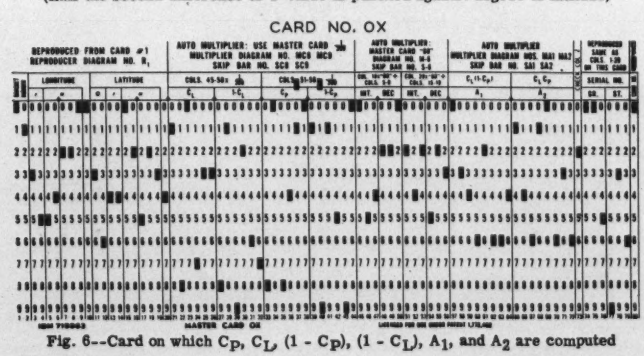
CARD NO. OX
REPRODUCED FROM CARD ⌀ 1
REPRODUCER DIAGRAM NO. R1
AUTO MULTIPLIER: USE MASTER CARD
MULTIPLIER DIAGRAM NO. MC4 MC5
SKIP BAR NO. SC8 SC9
AUTO MULTIPLY: MASTER CARD "BX" DIAGRAM NO. M-4 SKIP BAR NO. S-4
AUTO MULTIPLIER MULTIPLIER DIAGRAM NOS. MA1 MA2 SKIP BAR NO. SA1 SA2
REPRODUCED SAME AS COLS. 1-25 ON 1925 CARD
LONGITUDE
LATITUDE
SERIAL NO.
MASTER CARD OX
IBM 719063

Fig. 6--Card on which C_P, C_L, (1 - C_P), (1 - C_L), A_1, and A_2 are computed

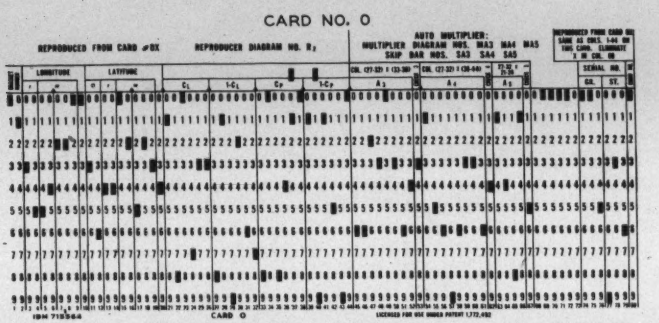

Fig. 7--A_3, A_4, and A_5 are computed on card O which is an extension of card OX

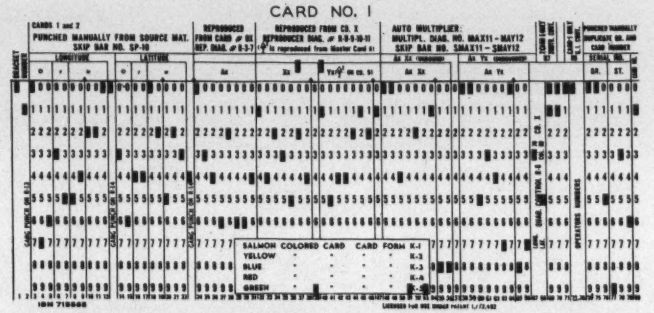

Fig. 8--Geographic position and serial number are punched on cards 1 and 2 by independent operators; X_1 and Y_1 are transferred from master-card X, A_1 is transferred from card OX, and products $A_1 X_1$ and $A_1 Y_1$ are computed on card 1

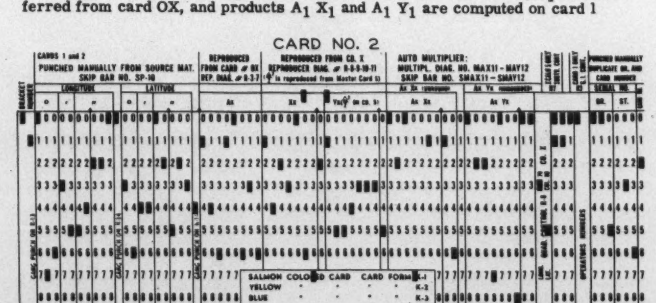

Fig. 9--Cards 1 and 2 are compared mechanically to determine whether same data were punched in the two cards by two respective card-punch operators; $A_2 X_2$ and $A_2 Y_2$ are computed on card 2

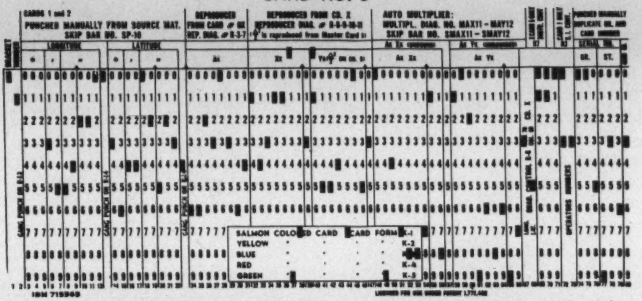

Fig. 10--Geographic position is transferred from either card 1 or card 2 onto cards 3 to 8, OX, and 0; A_3 X_3 and A_3 Y_3 are computed on card 3

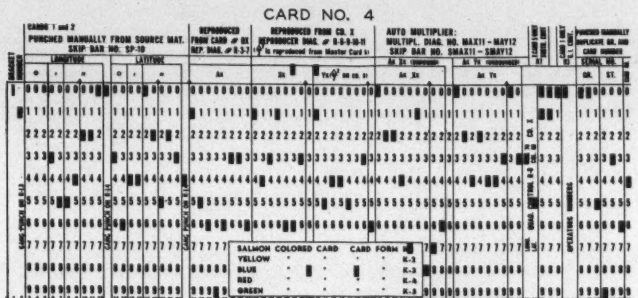

Fig. 11--A_4 X_4 and A_4 Y_4 are computed on card 4

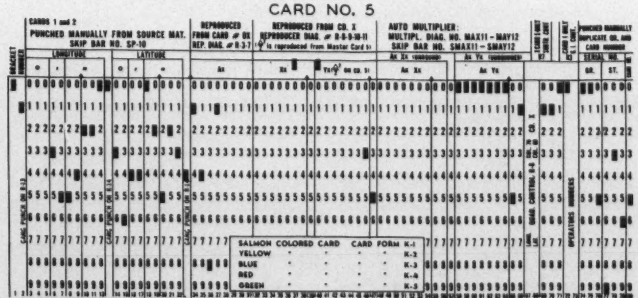

Fig. 12--A_5 is transferred from card 0, and the second difference of Y-values for latitude is transferred from second master-card (see Fig. 5) onto card 5 and $[-A(\Delta^2/2)]$ is computed

CARD NO. 6

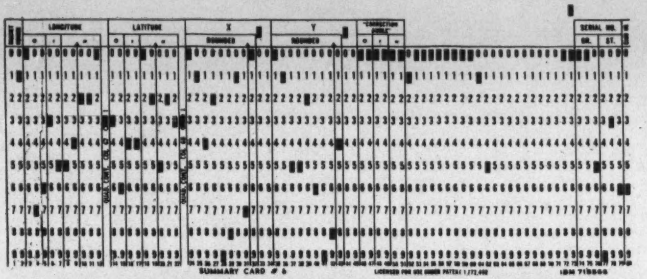

Fig. 13--X- and Y-values on card 6 are algebraic sums from cards 1 to 5 and are military-grid coordinates for point for which latitude and longitude are indicated (proper value of correction-angle is not shown in this illustration); card 6 is used to tabulate final results

CARD NO. 7

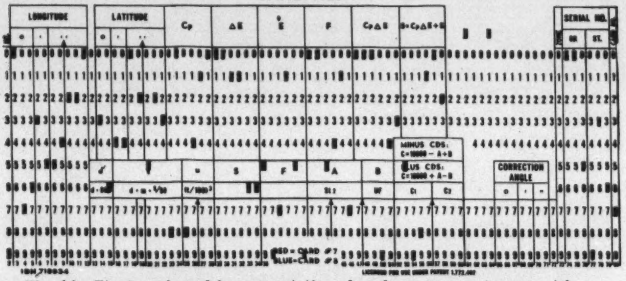

Fig. 14--First card used for computation of angle necessary to convert from geodetic to military-grid coordinates (only upper headings are used and lower headings are meaningless on this card)

CARD NO. 8

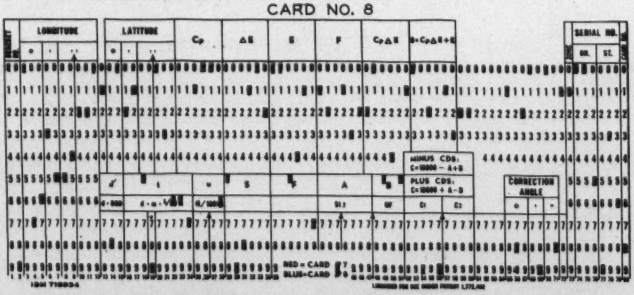

Fig. 15--Second card used for computation of azimuth-conversion angle (upper headings are meaningless and only lower headings are used on this card)

Where gisement is given in minutes of the angle, t = difference in minutes of longitude (without regard to sign) between the station and the central meridian; and ϕ = the latitude of the station.

Letting G represent the angle in minutes to be added to the geodetic azimuth to obtain the military-grid azimuth, the formula for this angle is G = 10800 - A + B, where the station is east of the central meridian, and G = 10800 + A - B where the station is west of the central meridian. In these formulas the values are as follows: A = t S; B = U F; S = sin ϕ; U = $(t/100)^3$ F; F = (a + b) c = $(100^3/24)$ $(\pi/180 \times 60)^2$ (sin ϕ - sin 3 ϕ); a = sin ϕ; b = sin 3 ϕ; c = $(100^3/24)$ $(\pi/180 \times 60)^2$ = 0.0035257; S = E + Cp ΔE; E = sine of the latitude of the southern limit of the five-minute quadrangle; ΔE = difference between sines of the latitudes of the southern and northern limits of the five-minute quadrangle; Cp = fractional distance of the station from the southern limit of the five-minute quadrangle.

The angle to be added to the geodetic azimuths to obtain military-grid azimuths is computed on cards 7 and 8. These cards are alike in appearance except that card 7 is red and card 8 is blue. The headings at the top are for card 7 and the headings in the lower half of the form are for card 8. For example, columns (35) to (40), inclusive, are used for E on card 7 and these same columns are used for F on card 8.

On card 7 the bracket number, minutes and seconds of longitude, degrees, minutes, and seconds of latitude, Cp, and the serial number are reproduced from card OX (see Figs. 6 and 14), and ΔE, E, and F are reproduced from a master-card (not shown). Card 1 is selected from the file by the collator and the degrees of longitude on it are punched in card 7. The values of latitude and longitude and the serial number are verified between cards 1 and 7. Cp ΔE and S are then computed.

On card 8 the bracket number, longitude, S, F, and serial number are reproduced from card 7. The difference in minutes of longitude between the station and the central meridian is computed, and from this the correction-angle, or the angle in minutes to be added to the geodetic azimuths to obtain military-grid azimuths is computed. This angle is then converted to degrees, minutes, and seconds, and punched in columns (65) to (71) on card 8 (see Fig. 15) from which it is transferred to columns (46) to (51), inclusive, on card 6.

Now the cards OX, 0, 1, 2, 3, 4, 5, 7, and 8 may be destroyed and only the summary card (card 6) need be kept in a permanent file. The tabulating machine prints the data which is on card 6. The station is identified by the serial number and the geographic position is proof-read against the original data.

The summary cards are sorted into 15-minute quadrangles and the tabulating machine prints the data from these cards. The stations are identified by the serial numbers and the geographic positions are proof-read against the original data.

No accurate estimate has been made as to how long is required for one person to convert from geographic to grid-coordinates, due to numerous difficulties which have arisen and which have no relation to the procedure. One major difficulty has been a rapid turnover in personnel on the project, and continual training of new operators. But the following facts may give an idea of the speed of this process. One military unit felt that it had achieved high efficiency in reducing the time for a computer to make the conversion from the geographic position to military-grid coordinates for one point in 12 minutes. Another claims that the conversion can be made in five minutes. Whether this speed can be maintained is questionable. Also this has to be done in duplicate by another computer as a check. In computing the C_P's and C_L's with the accounting machines, 1,800 cards can go through a multiplying machine in one hour with two multiplications and two additions being made on each card. Six hundred multiplications of A_1 X_1 are made in one hour. One person can operate five multiplying machines at once. No matter how many conversions involve the use of X- and Y-coordinates of a five-minute intersection, the value is looked up by a human eye only once, and the machines make all subsequent selections.

U. S. Coast and Geodetic Survey,
Washington, D. C.

COMPUTATION OF GEOGRAPHIC POSITIONS BY THE CALCULATING MACHINE

L. G. Simmons

The Coast and Geodetic Survey is charged with the establishment of the primary triangulation-control for the United States and its territories. For this reason the problem of computing geographic positions resulting from the triangulation is of considerable importance. Heretofore this work has been performed in this country with the use of logarithms only. For the purpose of increasing the speed and accuracy in the geographic position computation, a special method has recently been devised whereby the work can be done with the use of natural functions and the calculating machine.

The possibility of using the old method, by merely converting the functions into the natural form, was considered but quickly abandoned because the method is not readily adaptable to the use of the calculating machine. This is particularly so in the case of the latitude-differences.

In the old method, the difference of latitude was expressed in a power-series involving terms up to the fourth order. These terms contain three or more factors and include some of a very small order, making the computation in the natural form rather awkward. The difference of longitude, on the other hand, has been computed in a more direct manner and lends itself very readily to the calculating-machine method. No difference in theory for this operation is used in the new method.

The new method, in so far as the computation of the latitude-difference is concerned, is based on the solution of a right-angled spherical triangle. Let us call this triangle ABC and the corresponding opposite sides x, y, and s. A is the point whose position is known, B the point whose position is sought, and C the foot of the perpendicular from B to the meridian through A. The distance over which the computation is to be made is s, the meridian-distance between A and C is y, and the perpendicular from B to the meridian is x. x and y are computed as s sin A and s cos A with corrections, due to the fact that the triangle is spherical and not plane. These corrections are easily calculated, as it can be shown that the y-correction is proportional to the square of x and the x-correction is proportional to the square of y.

The basic table used in the method is that of the length of the meridian from the equator to as far north as the work is to be carried. This length is listed in a continuous form and tabulated for every minute of latitude. Now if the meridian-value for the latitude of point A is taken from the table and the distance y applied to it, the latitude for the point C can be determined. The problem now is that of computing the latitude-difference between C and A. As the spherical angle at C is 90°, the azimuth of the line CA will either be 90° or 270°. In any event, the sine of the azimuth will be one and the cosine will be zero. This difference of latitude is handled by the theory employed in the old logarithmic method. All terms involving the cosine of the azimuth drop out, leaving only the second, third, and fifth terms. The second term is the principal one and the only one of any significance for lines up to about 100 km. The effect of the third term can be entirely neglected, while the effect of the fifth term begins to take on significance when the line AB approaches 100 km.

The second term mentioned above, involves the second power of the length, as well as the factor to be taken out for the latitude of the starting point, in this case the point C. In order to avoid the taking out of the latitude of the point C, the factor used is listed against the y along the meridian which has been previously determined. The fifth term, when it becomes appreciable, is handled by another factor tabulated with the y along the meridian and a term involving the fourth power of the length. All of these factors are tabulated in the most convenient form possible and are of a magnitude designed to minimize any difficulty in handling the decimal point.

The difference in longitude is computed, in theory, as it was in the old logarithmic method. Two of the old logarithmic factors have been combined, however, and the result tabulated in the natural form. Corrections for the assumption that the arcs are proportional to the sines are handled as corrections in the natural form. The difference between the forward and back azimuth is also computed as in the logarithmic method, using a natural function again.

It is not the purpose of this paper to go into any great detail regarding the theory and proof of the formulas used. This will appear as an appendix to the tables when they become available.

Tables have already been computed for the latitude-range of the continental United States, using the foot as the unit. The computation of tables is now in progress for latitudes from the

equator to 75° with the meter as the unit. It is planned to combine these special tables with a table of natural sines and cosines in order that all the necessary data for the computation of geographic positions may be included in one comparatively small publication. This will be a minute-to-minute table, with differences per second. Special care is being taken to see that a complete computation can be made at one entry of the table with the exception of the sine and the cosine of the azimuth. All formulas for corrections, etc., will be repeated on each page to accomplish this purpose.

In general, the factors and functions have been extended one more figure than those in the logarithmic form. The computations resulting from the use of these tables should be of a slightly greater accuracy than heretofore.

U. S. Coast and Geodetic Survey,
Philadelphia, Pennsylvania

USE OF THE PRISMATIC ASTROLABE FOR ASTRONOMIC POSITIONS BY THE HYDROGRAPHIC OFFICE

L. M. Samuels

The prismatic astrolabe with a 60° prism was developed by French engineers in 1903. Later on, British engineers brought out a similar instrument with a 45° prism, for which certain advantages are claimed. The principles of both types are analogous in determining astronomic latitude and longitude by equal altitudes of heavenly bodies when the time of a prime-meridian, such as Greenwich, is known. This method of equal altitudes originated with Gauss, the noted astronomer, who in 1808 demonstrated that if the right-ascensions and declinations of three or more stars be known, and equal altitudes of these stars be observed at times recorded, then from these times there may be computed (1) the observed altitude, (2) the error of the chronometer on local time, and (3) the latitude of the observer. Nowadays, with radio time-signals, in addition to latitude, the longitude also may be deduced by this process of equal altitudes.

The first determination of astronomic position with the astrolabe by the Hydrographic Office was in Venezuela in 1938. Previously we used the meridian transit-zenith telescope. From actual observing with each, I am convinced of many and worth-while advantages of the astrolabe over the transit-zenith telescope, and without the sacrifice of precision. There is nothing at all complicated about the observations, computations, or adjustments of the astrolabe.

The French "geodetic model" of Claude and Driencourt, with 60°prism, which we use, weighs 30 pounds, for the instrument--with case and accessories, about 45 pounds--and can be carried by one man. Whenever possible, we build a pier for observing and for a permanent marker, but a tripod-support is part of the equipment, which serves its purpose well and weighs 11 pounds. The instrument is set up and adjusted without much difficulty or exertion, and the observer can be seated. No more care is required for leveling the astrolabe than for an ordinary surveyor's theodolite. Orientation in the meridian closely enough for a start is done with an attached magnetic compass and applying the local declination. Collimation, which the makers term "auto-collimation", is effected with two knurled screws on the exterior of the alidade, and but a moment's work. Being leveled, oriented, and collimated, there remains but to pour a small amount of mercury in the pan for an artificial horizon, and the observations are in order.

We, of the Hydrographic Office, in appreciation of our success with the 60° astrolabe, feel greatly indebted to Colonel BAGLEY, U.S. Army, to Mr. SHEA of the Massachusetts Institute of Technology, and to Mr. WELD ARNOLD, formerly of the Institute of Geographical Exploration, now a Major in the office of the Director of Photography, U.S. Army Air Corps, for the help they have all given us in astrolabe-work, and also for Major ARNOLD'S splendid compilation of a very comprehensive list of stars for each degree of latitude from 60° south to 60° north, without which our astrolabe-observations could hardly have been attempted. On occasions when no program of stars was prepared in advance we have read them off directly from Major ARNOLD'S catalogue, taking them in sequence as tabulated for local sidereal time and corresponding azimuth. A preselected list of stars to observe is, however, desirable, so as to get the proper distribution of azimuths in each quadrant, but no special preparation of observing programs, such as required for the transit-zenith telescope, is necessary in astrolabe-procedure. No reference to old catalogues, such as the Boss, need be made for the astrolabe as current star-publications suffice without having to work up star-positions to any date.

As to the dependability of the astrolabe, we had an excellent opportunity a year or so ago to verify this at the Naval Observatory by accepting for standard of comparison the astronomic position of the pier we used as determined by Naval Observatory astronomers. In latitude, two of our student observers with the astrolabe differed respectively 0".6 and 0" from the established value; in longitude each came within 1".1. An experienced observer in the same test checked to 0".2 in latitude and 0".5 in longitude. Mr. ENGLISH, who is very kindly assisting me here, received his instruction in the astrolabe last winter under adverse conditions of weather, permitting but three clear nights. Only seven days in all could be spared for the period of instruction, but nevertheless his determinations have been very gratifying with probable errors in six sets, 18 to 20 stars each, of 0".06 in latitude and 0".08 in longitude. No test for personal equations of the observers has been possible as yet, but it seems reasonable that the results of our observers at the Naval Observatory, as mentioned, would be even closer with a small correction to the longitude on assumption of a slight lag in the general or usual personal reaction. The makers of the astrolabe have developed a machine for testing personal equations which is reputed to be very efficient, but owing to war conditions we have been unable to get any of them.

Procedure in observing with the 60° astrolabe is simple and not difficult to learn. Our junior hydrographic engineers, without previous assignment to astronomical work, have received a fair

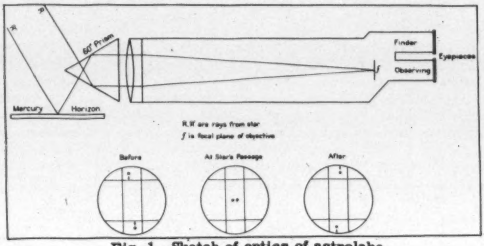

Fig. 1--Sketch of optics of astrolabe

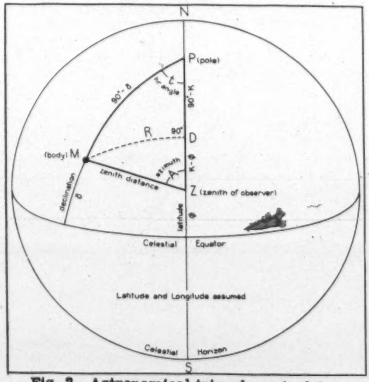

Fig. 2--Astronomical triangle, astrolabe

	By Napier's rules:
PZ = PD + ZD = 90° - φ	sin R = cos δ sin t
Let PD = 90° - k	sin K = (sin δ/cos R)
90° - k + ZD = 90° - φ	cos ZM = cos R cos(K - φ)
ZD = K - φ	sin A = (sin R/sin ZM)

understanding of the observing and computations in a few days, when pressed for time. As to flexibility of operations with the astrolabe, an astronomic-position expedition consisting of two officer observers completed 24 stations for latitude and longitude in less than six weeks. This time includes transportation by ship between stations, averaging about 60 miles apart, and time for landing gear through surf, making and breaking camp, and so forth.

Optics--The optical arrangement of the 60° astrolabe is illustrated in Figure 1. R and R′ are rays from a star. R passes normally through the upper face of the prism and is reflected from the lower face through the object glass to the focal plane of the objective at f. R′ is first reflected from the mercury-surface to the upper face, thence to f. The diagram is drawn to show the convergence of R and R′ at the instant the two star-images coincide at the altitude governed by the angle of the prism. The three figures at the bottom indicate the images on entering the field, at passage, and on leaving the field. Of the two eyepieces shown, the upper one is the finder eyepiece, of 30 diameters, having a field of 1° 36′, for training the alidade on the stars. A small prism actuated at will by a lever transmits the star-images from f to this finder-eyepiece and after centering the images therein the observer throws back the lever and the images are then set

ZENITH DISTANCES AND APPROXIMATE AZIMUTHS

Greenwich Sidereal Time of Observation Known

Place *Testigo Grande, Venezuela* Date *Aug. 11, 1941* Assumed Position ϕ_a 11° 22′ 00″ λ_a 63 07 15 Observer Computer *A.V. English*

Name of Star	*112 ε Aql			
Time from Chronograph	1 19 14.00			
Chronometer Correction (±)	+ 12 07.40			
G.S.T.	1 31 21.40			
Assumed Longitude (λ_a)	4 12 29.00			
L.S.T.	21 18 52.40			
Star's Right Ascension	19 22 34.37			
Hour Angle (H.A.) Time	1 56 18.03			
Hour Angle (H.A.) Arc	29 04 30.45			
Star's Declination (δ)	3 00 03.90			
Log Sin H.A.	9.686 5969			
(+) Log Cos δ	9.999 4041			
Log Sin R	9.686 0010			
R	29 01 53.22			
Log Sin δ	8.718 9243			
(−) Log Cos R	9.941 6870			
Log Sin K	8.777 2373			
K	+ 3 25 57.26			
Assumed Latitude (ϕ_a)	+ 11 22 00.00			
K − ϕ_a	7 56 02.74			
Log Cos (K−φ)	9.995 8230			
(+) Log Cos R	9.941 6870			
Log Cos Z.D.	9.937 5100			
Calculated Z.D.	30° 00′ 16.9″			
Observed Z.D.	30 00 00.0			
To Correction	16.9″			
Log Sin R	9.686 0010			
(−) Log Sin Z.D.	9.698 9700			
Log Sin Azimuth	9.987 0310			
Azimuth	256° 04′			
Azimuth, Star List	256°			

Fig. 3--Form for astrolabe-computations of zenith-distances and approximate azimuths (GST of observation known)

NHO-750

ASTROLABE COMPUTATIONS

LATITUDE AND LONGITUDE

GREENWICH SIDEREAL TIME OF OBSERVATION KNOWN

PLACE *Testigo Grande, Venezuela* ASSUMED LAT. *11° 22' 00"* ASSUMED LONG. *63° 07' 18"* ASSUMED Z.D. *30° 00' 00"*

SHIP OR EXPEDITION *U.S.S. Sumner* DATE, 1941 *Aug. 11* MEAN EPOCH OF OBSERVATIONS *0400 G.C.T.*

SIGNALS FROM *Annapolis* FREQUENCY *113 Kilocycles* OBSERVER *A.V. English* COMPUTER *A.V.E.*

INSTRUCTIONS

Let ϕ_a = assumed latitude, ϕ = true latitude sought, t = hour-angle, δ = declination, Z = zenith-distance, A = azimuth; and let R and K be auxiliary angles. Then, using Form 750-, Z and A may be computed from sin R = sin t cos δ, sin K = sin δ /cos R, sin A = sin R/sin Z, cos Z = cos (K - ϕ_a) cos R

The observations may be plotted with a scale and protractor on any blank sheet of paper; but it is more convenient to use the Astrolabe Plotting Sheet Form 750, on which one small division may be taken to represent any desired small arc of a great circle, as for example 0°.5.

From the origin, representing the assumed position, lines are drawn indicating the respective azimuths of the stars observed; and the length of each line, to scale, is made equal to the difference between the observed and computed values of the zenith-distance. This is the usual case, when the observed zenith-distance is less than the computed zenith-distance, refraction tending to reduce the observed value. In the opposite case, when the observed value is greater than the computed value, the azimuth-lines must be drawn in the opposite directions.

At the outer ends of the azimuth-intercepts, position-lines perpendicular to the intercepts are drawn, and within the polygon of position-lines a circle is drawn, by trial, having a center and a radius such that, as nearly as possible, all position-lines will be tangent to the circumference.

This center is the position by observation. Its vertical or Y-coordinate is the difference in arc between the assumed and observed latitudes. Its horizontal or X-coordinate, when multiplied by the secant, or divided by the cosine, of the assumed latitude, is the difference in arc between the assumed and observed longitudes.

Note 1--To avoid a circle of large radius, due to a high initial uncertainty in the position of a station, observe with the astrolabe a single bright star on both sides of the meridian. At the mean of the transit-times the LST is equal to the star's right-ascension, whence by a comparison of the GST of the same instant the approximate longitude may be found. The half-interval between transits gives the hour-angle t. This, substituted in the first two formulas, gives R and K; which together with the instrumental value of Z, substituted in the third formula, gives the approximate latitude.

Note 2--A complete list of instruments and their numbers should be attached to the observations.

CLOCK CORRECTIONS

Greenwich Date,	h	m	s	h	m	s	h	m	s
G.C.T. of Signal	2	59	37.00	3	56	30.00	5	00	00.00
G.S.T. of Greenwich 0^h	21	16	15.91	21	16	15.91	21	16	15.91
Corr. for Int. since 0^h	+		29.51	+		38.86	+		37.28
G.S.T. of Signal	00	16	22.42	1	13	24.76	2	17	05.19
Clock Time of Signal	00	04	14.99	1	01	17.35	2	04	57.81
Clock Corr. on G.S.T.	+00	12	07.43			07.41			07.38
at Signal (F-, S+)									

Average Hourly Rate between Signals 0.025 | Interval between Signal and Mean Epoch | Change in Error in Interval

Gaining / Losing s 0.025 × Hours 0.75 = s 0.02 Gaining / Losing

LATITUDE DIFFERENCE	Divisions	° ′ ″	
Assumed Latitude, Φa		11 22 00.0	
Y-coordinate (N, S)	8.5 =	+ 8.5	
Observed Latitude		11 22 08.5	N

LONGITUDE DIFFERENCE	Divisions	° ′ ″	Log
X-coordinate (W, E)	19.9		1.298 8531
Log Cos Lat. (subtract)			9.991 3733
or			
Nat. Sec Lat. (multiply)			1.307 4398
			20.2
Corr. to assumed Long.		-20.3	
Assumed Longitude		63 07 18.0	
Observed Longitude		63 06 54.7	W

COMPUTER'S NOTES:

Fig. 4--Form for astrolabe-computations of latitude and longitude (GST of observation known)

to appear for observing in the lower eyepiece of 80 diameters and 36' field.

Astronomical triangle--The astronomical triangle concerned in the computation is projected in Figure 2 on the plane of the observer's horizon extended to the celestial. NS is the observer's meridian through his zenith-point Z, and P the elevated pole. M is the body observed, and δ its declination. R by construction is a perpendicular from M to the meridian at D.

The assumed longitude, the Greenwich sidereal time, and the body's right-ascension are known, from which the body's hour-angle (t) is deduced. The observer's assumed latitude and the declination of the body are known. The two spherical right-triangles PMD and DMZ are successively solved, from which the values of ZM the zenith-distance, and A the azimuth of the body, are computed in relation to the assumed position.

Computations--Each vertical column of the form shown in Figure 3 provides space for the solution of one star in accordance with the formulas of Figure 2. The form allows computation of five stars, the steps for one star being filled out.

Figure 4 is the reverse side of the previous form. All necessary calculations are confined to the two sides of the form-sheet. The computations and plotting of one set of stars may be done easily in a day.

As already mentioned in the solution of the astronomical triangle, the zenith-distances and azimuths of the stars are computed from assumed coordinates. The position sought is then plotted graphically, using the various zenith-distance differences and azimuths in somewhat

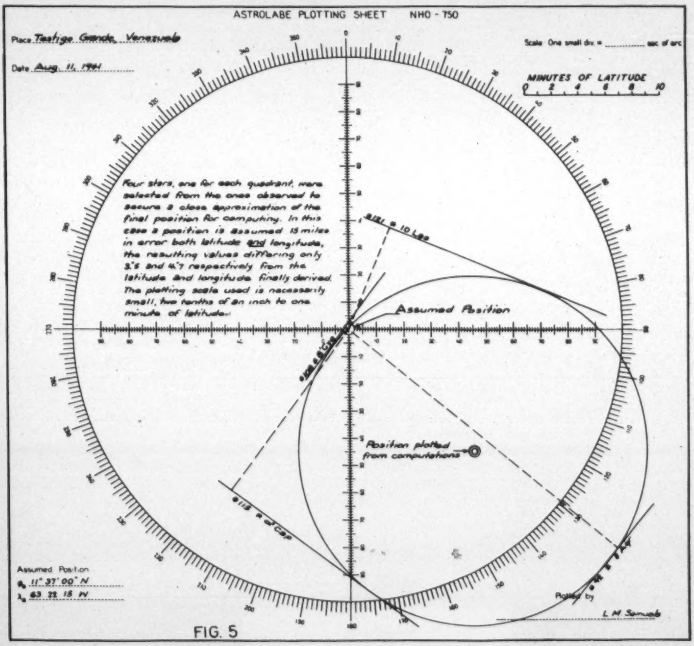
ASTROLABE PLOTTING SHEET NHO - 750
Place Testigo Grande, Venezuela
Date Aug. 11, 1941
Scale One small div. = ... sec. of arc
MINUTES OF LATITUDE
0 2 4 6 8 10
Four stars, one for each quadrant, were selected from the ones observed to secure a close approximation of the final position for computing. In this case a position is assumed 15 miles in error both latitude and longitude, the resulting values differing only 3.5 and 4.7 respectively from the latitude and longitude finally derived. The plotting scale used is necessarily small, two tenths of an inch to one minute of latitude.
Assumed Position
Position plotted from computations
Assumed Position
ϕ_a 11° 37' 00" N
λ_a 63 22 15 W
Plotted by L. M. Samuels
FIG. 5

Fig. 5--Astrolabe plotting sheet, Testigo Grande, Venezuela, August 11, 1941

similar manner that lines of position in navigation are used, except that for the astrolabe the difference between observed and computed zenith-distance is plotted instead of the difference of altitude.

Preliminary position--A preliminary computation is first made from four stars of an observed set in order to get an approximate position within 10″ or 15″ of the final position for use

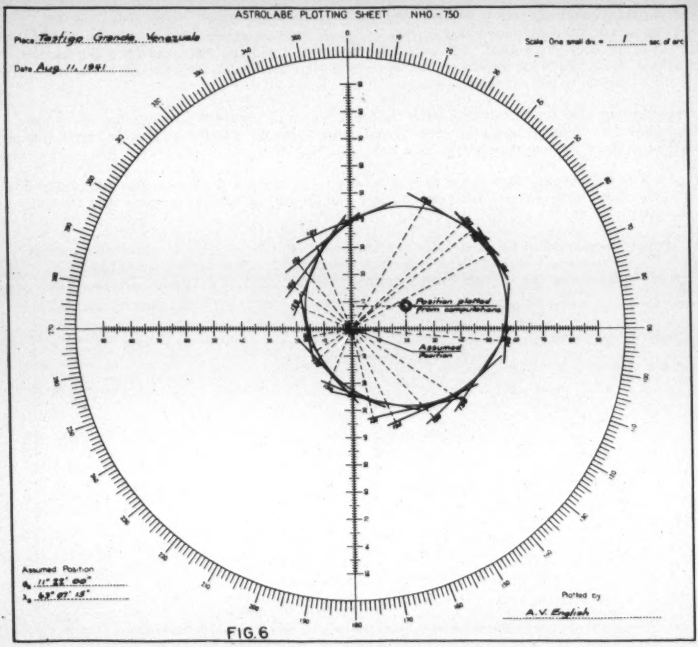

FIG. 6

Fig. 6--Second astrolabe plotting sheet, Testigo Grande, Venezuela, August 11, 1941

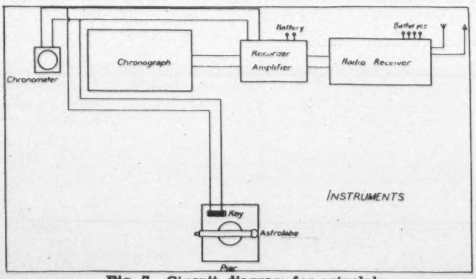

Fig. 7--Circuit-diagram for astrolabe

in the final computations and plotting. The four stars are selected in azimuth as nearly 90° apart as possible, and with the latitude and longitude to the nearest minute from available maps or charts, the zenith-differences and azimuths are computed in the same manner and form as the final position. Illustrating how the approximate position is derived, Figure 5 was prepared with the latitude and longitude purposely in error about 15 miles. This position is represented at the center of the diagram. The four dotted lines are the plotted azimuths of the four selected stars. The normals to these dotted lines are drawn at respective zenith-difference intercepts from the

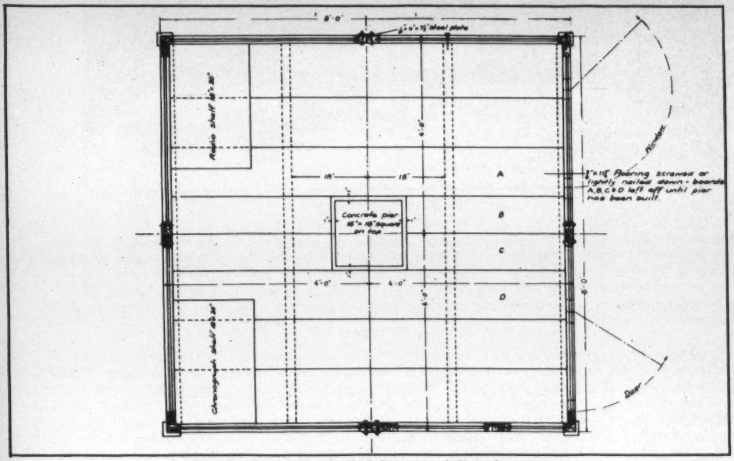

Fig. 8--Portable shelter for astrolabe, plan view

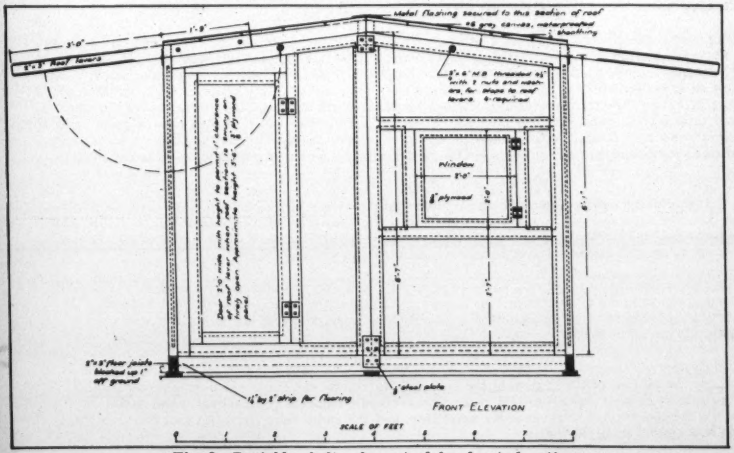
Metal flashing secured to this section of roof
3'-0"
1'-9"
2"×3" Roof lavers
Window
3'-0"
6" plywood
6'-5"
2'-3"
5'-5"
Door 2'-0" wide, with height to permit 1" clearance of roof layers when roof height is 6'-5" (only)
2"×5" floor joists blocked up 1" off ground
1½" by 5" strip for flooring
FRONT ELEVATION
SCALE OF FEET
0 1 2 3 4 5 6 7 8

Fig. 9--Portable shelter for astrolabe, front elevation

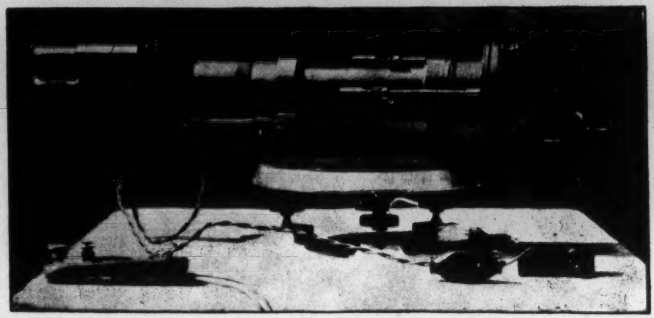

Fig. 10--View of astrolabe

center of the diagram, and by construction are tangents to a circle the center of which is the observed point. The scale of Figure 5 is 0.2 inch to 1′ of latitude, and the derived position proved to be within 5″ of the final position. A close value of the longitude may be found directly if any star of the set is observed on both sides of the meridian; in such case the longitude is the difference between the mean of the Greenwich sidereal times of the star's passages and the star's right-ascension.

Final observed position--The diagram of Figure 6 is an example of the final plotting. The preliminary position, found from the four selected stars of the set, and shown at the center of the diagram, becomes the assumed position for the final computations and plotting. The azimuth-lines of the various stars of the set, including the four selected stars recomputed for the new assumed position, are shown with their corresponding normals, these normals being tangents to a circle the center of which is the final observed position and indicated by the two small concentric circles. The value of this final observed position is referred to the known assumed position, the latitude-correction in arc being scaled direct, the correction for longitude arc being the scaled difference times the secant of the latitude.

Opinions differ as to the number of stars which should be observed for each set. Our system is, whenever possible, to control the set with three radio time-signals, an hour apart, and within this two-hour period to observe as many stars as practicable, consistent with careful work. Generally an excess number of stars are observed than are utilized in the computations, but it permits a selection for distributing the position-circle tangents to advantage in the quadrants, and also provides additional stars for checking if needed. We prefer not less than five stars to each quadrant. As a rule, stars closer than 10° to the meridian are avoided as they change too slowly in altitude for accurate timing, and time is the deciding element for precision in astrolabe operations.

A few minutes before commencing the observations, it is advisable to take out several stars from the catalogue and point on them to check the compass-orientation of the azimuth-circle, and also for adjusting the focus of the observing eyepiece--this focus must not be altered during any set as so doing will materially vary the constant measure of the altitude.

A unique feature in observing with the prismatic astrolabe is that the two images of the star, as seen in the telescope, approach from opposite directions, and therefore at twice the apparent motion, so if there be any displacement in the observer's estimate of the coincidence of the images, his error is halved.

Instruments--Figure 7 shows our usual arrangement of instruments for astrolabe-observations. At the bottom of the Figure is the pier with astrolabe and observer's break-circuit key. In the upper part of the diagram at left is the break-circuit sidereal chronometer, and thence to right the chronograph, radio-recorder amplifier, and the radio receiver. Current for electrical needs is supplied from dry cells.

Astrolabe-shelter plan--Figure 8 is the plan of a portable type of shelter we use for the astrolabe. It is 8 feet square and 6-1/2 feet high and designed so that it may be set up at the same time the pier is being built. The sides and roof are each in two sections, 4 feet wide and 6 to 8 feet long, and in the erection are bolted together in place. The paneling is 3/8-inch plywood rabbetted into 2-inch by 3-inch white-pine framing.

Astrolabe-shelter elevation--Figure 9 is an elevation of the portable shelter. The roof is in two sections as mentioned. Each section is hinged at the side and can be thrown back with two levers to clear the ceiling for observing. All sections of the structure are thoroughly waterproofed and painted, and the whole may be towed as a raft in the water for landing if desired. There is sufficient room inside the shelter for a couple of cots and also for the observer's living and computing quarters.

The Hydrographic Office has adopted the astrolabe for astronomic-position origin. This is in keeping with a progressive policy to constantly improve our methods in field-surveys, and likewise in the compilation, construction, and reproduction of surface- and air-charts. A keen interest is always manifested in new equipment and procedures, whether developed elsewhere or by our own personnel.

U. S. Hydrographic Office,
Washington, D. C.

GRAVITY-OBSERVATIONS IN PERU AND COLOMBIA

Carl I. Aslakson

In view of the present wide-spread interest in Pan-American affairs and the need, long recognized by geodesists, for base gravity-stations in the equatorial belt of South America, a brief description of a recent cooperative gravity-expedition in Peru and Colombia may be of interest.

The earliest attempts at the measurements of gravity in South America were those of BOUGUER in the early part of the 18th Century. In his report, published in 1749, he describes the methods and results of his work in Peru and Ecuador in determining the figure of the Earth. BOUGUER determined the length of a filar-suspension seconds pendulum at three points in Ecuador at elevations of 0, 9,400, and 15,600 feet. His results, of course, have no quantitative value.

In the early part of the 20th Century another French Commission, the Service Géographique de L'Armée, also determined gravity in several parts of Ecuador. There seems to be some doubt as to the accuracy of this work, but we have reduced a few of the Ecuadorian values for the purpose of comparing the isostatic anomalies with those in Peru and Colombia.

The preliminary negotiations for the present project were concluded between the State Departments of the three governments late in 1940. The United States Coast and Geodetic Survey appointed the speaker and PHILIP T. HANSEN, Principal Scientific Aid, as the North American members of the Commission. The details of organization, including the preparation of the instrumental equipment, which was loaned by the United States Coast and Geodetic Survey, were completed in January, 1941. Two sets of the Brown pendulum gravity-apparatus were used for simultaneous observations. The Brown apparatus is the standard pendulum-instrument of the United States Coast and Geodetic Survey and has been described in previous papers before the Section of Geodesy.

The following organizations and persons were designated by their respective governments to cooperate with the Commission:

Peru	El Servicio Geográfico del Ejército Coronel BERNARDINO G. VALLENAS, Director
Colombia	El Instituto Geográfico Militar y Catastral Dr. HERNANDO POSADA CUELLAR, Director

The success of the Expedition was due in a large measure to the interest and efficient cooperation of these two distinguished engineers.

Other members of the commissions were:

Table 1--Principal facts at gravity-stations

Chief of party:

[Base-value at Washington, Commerce Building, determination of 1933, is 980.118]

Station	Latitude, φ	Longitude, λ	Elevation	Obs'd gravity, g	Theoretical gravity, γ_o	Correction	
						Elevation	Topography, Zone o
	° ′	° ′	meters	gals	gals	gal	gal
PERU							
Lima, Servicio de trasmissiones	-12 01.1	77 02.3	143.6	978.289	978.2723	-0.0443	+.0109
Piura	- 5 11.9	80 38.1	35.3	978.084	978.0913	-0.0109	+.0040
Trujillo	- 8 07.0	79 02.3	29.4	978.095	978.1517	-0.0091	+.0007
Huaras	- 9 31.9	77 32.1	3071	977.228	978.1902	-0.9476	+.3320
Ica	-14 04.6	75 30.2	405.9	978.238	978.3537	-0.1253	+.0442
Chala	-15 49.0	74 18.5	14.0	978.452	978.4317	-0.0043	-.0024
Tacna	-18 01.0	70 15.0	557.1	978.298	978.5418	-0.1720	+.0567
Juliaca	-15 30.0	70 06.9	3825.2	977.325	978.4169	-1.1800	+.4286
Anta	-13 28.6	72 09.1	3421.9	977.339	978.3287	-1.0556	+.3790
San Jerónimo, North Base	-11 56.6	75 18.7	3245	977.285	978.2696	-1.0011	+.3593
South Base	-12 00.6	75 14.3	3248	977.288	978.2720	-1.0021	+.3594
COLOMBIA							
Buenaventura	3 53.9	77 04.7	5.1	977.998	978.0728	-0.0016	+.0003
Popayán	2 26.5	76 36.0	1757.7	977.602	978.0584	-0.5425	+.1950
Cali	3 27.5	76 31.1	996	977.861	978.0677	-0.3074	+.1104
Bogotá	4 38.5	74 03.9	2591.8	977.404	978.0827	-0.7998	+.2853
Bucaramanga	7 08.5	73 07.8	1117	977.820	978.1286	-0.3448	+.1214
Barranquilla	11 01.0	74 47.8	28.5	978.245	978.2371	-0.0088	+.0033
Medellín	6 14.9	75 33.6	1497.5	977.753	978.1100	-0.4623	+.1658
Ibagué	4 26.4	75 14.0	1252	977.715	978.0799	-0.3865	+.1280
Armenia	4 31.9	75 41.0	1514	977.732	978.0812	-0.4673	+.1668
Pasto	1 13.2	77 16.9	2592	977.386	978.0513	-0.7998	+.2863
Ipiales	0 49.5	77 38.3	2890	977.252	978.0500	-0.8917	+.3207
Villavicencio	4 08.8	73 37.3	495	977.860	978.0760	-0.1528	+.0519
Puerto López	4 05.2	72 56.9	216	978.002	978.0751	-0.0667	+.0244

Peru — Dr. ALFRED ROSENBLATT, Professor of Geodesy and Geophysics, San Marcos University, Lima

Dr. CARLOS BASADRE, Professor of Geodesy, Engineer's School, Lima

Columbia — Dr. DARIO ROZO M., Chief of the Section of Geophysics of the Instituto Geográfico, Bogotá

Dr. TOMAS APARICIO, Engineer, Instituto Geográfico, Bogotá

A Captain of Engineers was designated in each country to accompany the Expedition and to make all contacts and all arrangements for transportation and other expenses.

Capitán JOSÉ SAN MIGUEL was assigned to the party in Peru and Capitán GERARDO CABRERA A. in Colombia.

Certain difficulties were encountered owing to climatic conditions. Temperatures were extreme, being in general solely a function of the altitude. Consequently, temperatures frequently ranged from very hot to very cold several times in a single day. Humidity at the coastal stations was always high and caused some trouble in the electrical circuits.

The available electric power-supply is variable. Some plants deliver alternating and others direct current. The voltages range from 90 to 240 volts and the frequency from 45 to 65 cycles. In some cities separate plants with different characteristics and operated by separate organizations, supplied power in various parts of the city. Since the instrumental equipment operated at 110 volts and 60 cycles, it was necessary to provide our own power-supply in many places. Hence, the addition of heavy-duty transformers, gasoline charging-units, electronic and rotary converters, and many storage-batteries made the equipment far heavier and bulkier than that ordinarily carried

in Peru and Colombia, 1941 [Potsdam System]

C. I. Aslakson

International formula: $\gamma_o = 978.049\,[1 + 0.0052884\,\sin^2\phi - 0.0000059\,\sin^2 2\phi]$ gals

to theoretical gravity for				Anomaly					
Indirect effect	Topography and compensation			Free-air, $g - \gamma$	Bouguer, $g - \gamma'$	Isostatic (Pratt-Hayford)			
	Depth 56.9 km	Depth 96 km	Depth 113.7 km			Indirect, $g - \gamma_c{}^i$	56.9 km, $g - \gamma_c$	96 km, $g - \gamma_c$	113.7 km, $g - \gamma_c$
gal	gal	gal	gal	gal	gal	gal	gal	gal	gal
-.0036	-.0429	-.0420	-.0398	+.061	+.050	+.107	+.104	+.103	+.101
-.0028	+.0057	+.0145	+.0186	+.004	.000	-.008	-.002	-.011	-.015
-.0035	-.0494	-.0475	-.0447	-.048	-.048	+.003	+.002	.000	-.003
-.0072	+.0141	+.0691	+.0889	-.015	-.347	-.076	-.029	-.084	-.104
-.0040	-.0297	-.0264	-.0234	+.010	-.035	+.040	+.039	+.036	+.033
-.0032	-.0203	-.0143	-.0119	+.025	+.027	+.042	+.045	+.039	+.036
-.0050	-.0791	-.0842	-.0835	-.072	-.128	+.017	+.007	+.012	+.012
-.0083	+.0229	+.0522	+.0656	+.088	-.340	+.044	+.065	+.036	+.022
-.0077	+.0152	+.0526	+.0668	+.066	-.313	+.021	+.051	+.013	-.001
-.0076	+.0204	+.0648	+.0819	+.016	-.343	-.041	-.004	-.048	-.065
-.0076	+.0257	+.0686	+.0849	+.018	-.341	-.043	-.008	-.050	-.067
-.0033	-.0245	-.0234	-.0220	-.073	-.074	-.046	-.049	-.050	-.051
-.0055	+.0040	+.0313	+.0413	+.086	-.109	+.060	+.082	+.055	+.045
-.0046	-.0107	+.0027	+.0085	+.101	-.010	+.103	+.111	+.098	+.092
-.0058	+.0604	+.0954	+.1075	+.121	-.164	+.032	+.061	+.026	+.014
-.0045	-.0077	+.0062	+.0119	+.036	-.085	+.034	+.044	+.030	+.024
-.0023	+.0384	+.0511	+.0554	+.017	+.013	-.032	-.022	-.034	-.039
-.0049	+.0072	+.0336	+.0432	+.105	-.060	+.077	+.098	+.072	+.062
-.0052	-.0493	-.0286	-.0208	+.022	-.106	+.055	+.071	+.050	+.042
-.0052	-.0099	+.0122	+.0208	+.118	-.049	+.111	+.128	+.106	+.097
-.0058	+.0750	+.1135	+.1267	+.134	-.152	+.027	+.060	+.021	+.008
-.0063	+.0822	+.1267	+.1418	+.094	-.227	-.027	+.012	-.033	-.048
-.0042	-.0516	-.0483	-.0457	-.063	-.115	-.011	-.012	-.015	-.018
-.0033	-.0201	-.0250	-.0259	-.006	-.031	+.022	+.014	+.019	+.020

in the field in the United States. The total weight of the instrumental equipment transported in the field amounted to about 3,500 pounds.

In spite of the weight and bulk of the instruments, no serious transportational difficulties were encountered. This was due to a fine network of well-engineered principal highways in Peru and to a combination of efficient transportation-systems in Colombia.

In Peru all transportation was handled in trucks and automobiles of the War Department. Although the roads were literally "hung" on the precipitous sides of the Andes Mountains, the grades are so designed that heavy trucks can negotiate them without difficulty. At times a road distance of 50 km is necessary to cover a horizontal straight-line distance of six to eight km. The natural scenery can best be described by the words "stupendous" and "awe-inspiring." The altitudes along the highways frequently reached 14,000 to 16,000 feet. Fortunately, the American members of the Expedition escaped the effects of the dread altitude illness of the Andes, known as soroche. Landslides block the steeper portions of the Peruvian highways during the rainy months of February, March, and early April, but traffic is usually opened after intervals varying from a few hours to a week. On some switchbacks a single slide will cut the highway on many different levels.

Transportation-methods in Colombia included highways, railroads, and river boats. An efficient network of airways covers Colombia, but this proved to be of little value to the Expedition owing to the weight of the instrumental equipment. The transportation by rail and bus is rapid and the highways are good, all-weather roads. The river voyage on the Magdalena River to Barranquilla required the longest time. Frequently at low states of the river, traffic is completely blocked for the larger steamers.

With the exception of the two San Jerónimo Base stations in Peru, gravity-stations in both countries were always located in public buildings, such as universities, cuartels, post-offices, or other government or municipal edifices. This enabled the party to live in hotels rather than in camp. Most of the Colombian hotels were excellent, and a new Government program of tourist hotel-building is rapidly providing fine hotel accommodations in all the larger cities of Peru.

Results

A total of 24 basic stations were established in all, 11 being in Peru and 13 in Colombia. An excellent geographical distribution was obtained, the latitudes ranging from 18° south to 11° north. The station at Ipiales, Colombia, was located at latitude 0° 49′ north. Elevations above sea-level reach 12,550 feet at gravity-station Juliaca in the Peruvian Andes north of Lake Titicaca.

Owing to uncertainties of elevations many of the anomalies may also be uncertain. The elevations obtained in the interior of Peru were nearly all determined by trigonometric methods over

Fig. 1

triangulation-arcs, while in Colombia they were practically all determined by the hypsometer, an instrument invented by the Colombian naturalist, FRANCISCO JOSÉ DE CALDAS and used extensively in Colombia for determining the elevation by means of temperature of the boiling-point of water. Likewise, topographic corrections may change considerably when better maps are available.

In Figure 1 the stations established during this Expedition are shown by a solid black dot. In order to make the picture more complete the gravity-at-sea stations determined with the Vening-Meinesz instrument between 1926 and 1938, and a few of the early French determinations, are shown with different symbols.

In spite of the paucity of observations I have attempted to show the general trends by isoanomaly-curves. The isostatic anomalies are based on the 113.7-km depth of compensation.

The outstanding features are the negative trough along the coast in Peru, the steep gradient to the +101-milligal positive at Lima, and the positive ridge with its steep gradient toward the Coast in Colombia. The negative trough in Peru follows in general the axis of the Cordillera Central or middle range. In Colombia the positive ridge generally parallels the axis of the Cauca Valley. This ridge terminates abruptly between Pasto and Ipiales. It is in this vicinity that the three ranges of Colombia converge into a single range diverging again into three ranges once more in northern Peru.

It is interesting to note that the mountain masses in the southern part of Peru appear to be nearly compensated. Station Juliaca on the shores of Lake Titicaca at an elevation of 3,825 meters has an anomaly of +22 milligals while the coastal stations, Chala and Tacna, have anomalies of +36 and +12, respectively. Incidentally, the Servicio Geográfico del Ejército reports a deflection of the vertical of about 75″ between Tacna and Juliaca.

In Colombia two stations were established at Ibagué and Armenia which are respectively east and west of the central Cordillera and between which the Instituto Geográfico has found a deflection of the vertical of 57″ in a distance of 60 km. An excellent paper describing an investigation of this deflection has been written by Dr. JOSÉ IGNACIO RUIZ [see Revista de la Academia Colombiana de Ciéncias Exactas, Físicas y Naturales, v. 3, No. 12].

For the 113.7-km depth of compensation the largest anomalies in Peru are the +101 milligals at Lima and the -104 milligals at Huarás. Huarás is about 2-1/2° north of Lima and is almost 3,000 meters higher. Lima is, of course, a focal center of great seismic disturbances, and Huaras was almost totally destroyed with heavy loss of life by a landslide probably induced by an earthquake about six months after we occupied the station.

It is also interesting to note that the station at Pasto, Colombia, located at the foot of the Volcano Galera, has an anomaly of +8 milligals. This volcano was last active in 1935 when heavy clouds of smoke were emitted. At Ipiales, about 40 miles southwest, the anomaly is -48 milligals. In the region just to the north of Ipiales there have been heavy seismic disturbances including several very destructive quakes in recent years.

In summarizing the anomalies, it may be noted that the mean of the anomalies with regard to sign is reduced to +8 milligals for the 113.7-km depth of compensation while it is +36 and +16 for the 56.9-km and 96-km depths, respectively.

The need for more observations in the entire area is at once apparent from an inspection of the map. We have no stations east of the eastern range in Peru and only two stations, Villavicencio and Puerto López, east of this range in Colombia. Reliable observations are needed in Ecuador and determinations at sea are needed to the westward of Lima to determine the limits of the positive area.

We still lack sufficient observations in the northern part of Colombia and in southern Panama to settle the question as to whether the characteristic trough which parallels the north coast of South America bends to the southwest and crosses northern Colombia. Stations on both land and sea are needed.

When one compares the outstanding features of the iso-anomaly map with the regions of seismic activity, one wonders what a gravity-survey of northern Chile might reveal.

U. S. Coast and Geodetic Survey,
Washington, D. C.

RECENT PROGRESS IN GEODETIC SURVEYS OF THE UNITED STATES COAST AND GEODETIC SURVEY

H. W. Hemple

During the past year the activities of the Division of Geodesy of the United States Coast and Geodetic Survey have been principally concerned with surveys in certain strategic areas as requested by the War Department.

The fundamental triangulation-net of the United States as of March 1, 1942, is shown in Figure 1. The horizontal-control activities on the West Coast during the past year have consisted of triangulation in Washington, Oregon, and California. The work in Washington consisted of first-order triangulation along the eastern shore of Puget Sound from Seattle to Bellingham, an arc of first-order triangulation along the Yakima Valley extending from the Columbia River to the vicinity of Wenatchee, and a connection between coastal triangulation in the vicinity of Grays Harbor.

The work in Oregon is a coordinating scheme of triangulation along the Willamette Valley, triangulation in the vicinity of Tillamook and in the vicinity of Baker, and a detailed triangulation-scheme along the Columbia River from Pasco, Washington, to The Dalles, Oregon.

The horizontal-control surveys in California consisted of a triangulation-scheme in the Humboldt Bay Region coordinating coastal control, triangulation between Palmdale and Santa Barbara, triangulation in the Cholame Region, and an investigation by triangulation of movements due to earthquake-disturbances in the vicinity of El Centro, California.

In the middle west triangulation has been accomplished in Minnesota from Grand Rapids to the International Boundary, in North Dakota along parallel of latitude 47° 30′ north from the Minnesota Boundary to the Montana Boundary, along the Nebraska-South Dakota Boundary between longitude 103° west and longitude 104° west. Triangulation has also been accomplished in Arkansas along parallel of latitude 33° 30′ and in Texas along meridian 95° 20′ west,from Crockett to Houston.

Triangulation has been accomplished in Virginia from the North Carolina Boundary near Danville and extending northeastward to the vicinity of Fredericksburg. Work has also been accomplished from Petersburg north to Leesburg and from Williamsburg north to St. George, Maryland.

In West Virginia triangulation-surveys have been extended westward from Winchester, Virginia, to Clarksburg, West Virginia, and from White Sulphur Springs northward along meridian 80° 20′ west,to the Pennsylvania Boundary.

In Pennsylvania triangulation-surveys were made on a cross-arc in the vicinity of Altoona, extending from Harrisburg to Johnstown and from Kylertown to the Maryland Boundary.

Triangulation and traverse were extended along the Atlantic Coast from Portsmouth, New Hampshire, to Portland, Maine, and in the interior of Maine triangulation was provided from Skowhegan to Van Buren near the Canadian Boundary.

Triangulation in the interior of Alaska as accomplished to date is shown in Figure 2. In addition to the work shown, arcs of third-order accuracy extend along the coast and out to the westward into the Aleutian Islands.

In Alaska during the past year we have provided triangulation from Valdez along the Richardson Highway to the Alaskan range. This control will be extended this next season to Fairbanks and thence along the Alaskan Railway to Broad Pass, where a connection will be made to existing surveys. During the past season 88 stations were occupied and eight base-lines measured.

The first- and second-order level-net of the United States as of March 1, 1942, is shown in Figure 3. During the past season three multiple-unit leveling parties have been in the field. One party operated in Oregon along the coast from the California Boundary to the Columbia River, thence along the south bank of the river to The Dalles. This party also operated from Pendleton, Oregon, to Pocatello, Idaho, and from Vancouver, Washington, to Kelso, Washington, along the north bank of the Columbia River. This party at present is working in the Cholame Region in southern California.

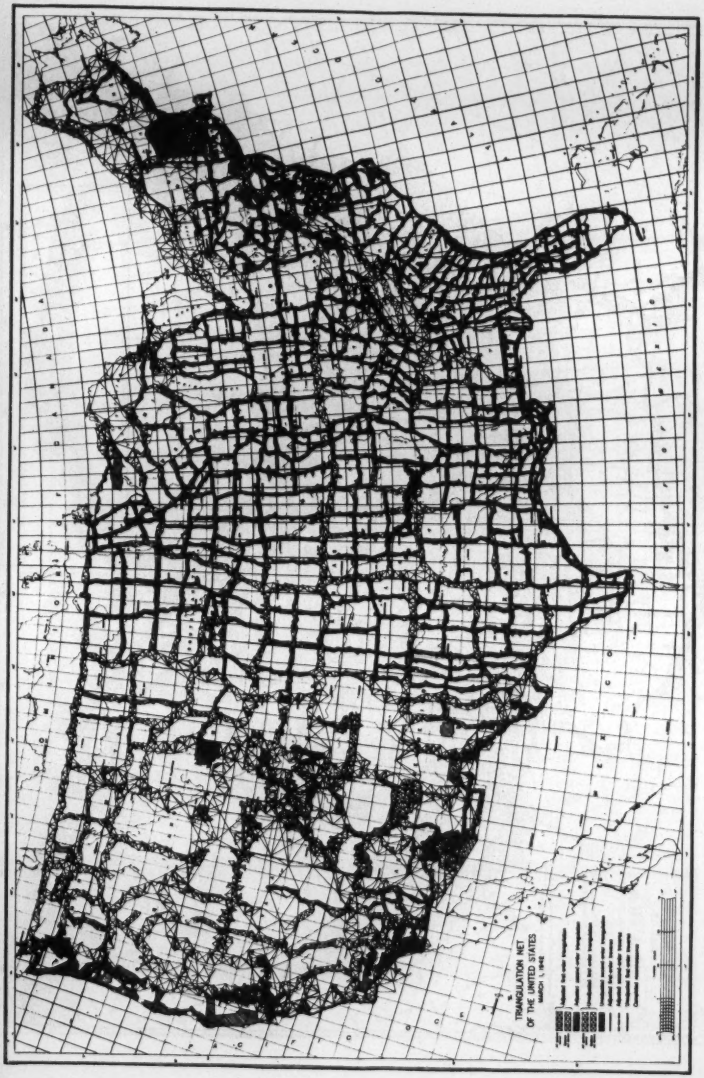

Fig. 1.--Triangulation-net, United States, March 1, 1942

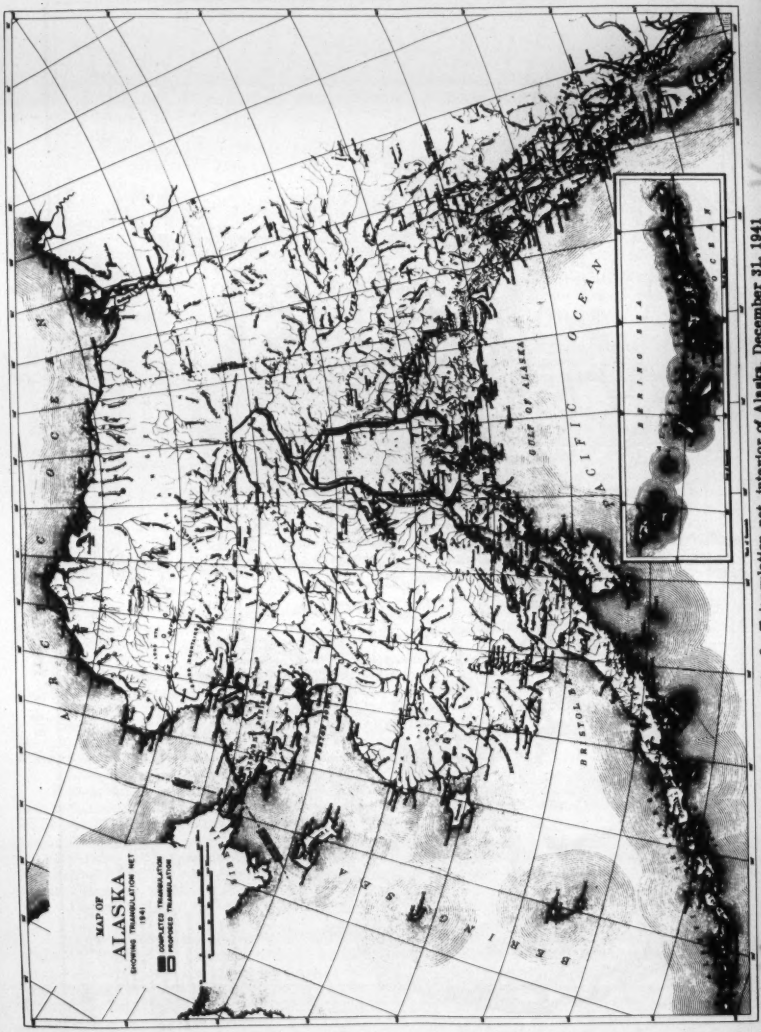

Fig. 2.--Triangulation-net, interior of Alaska, December 31, 1941

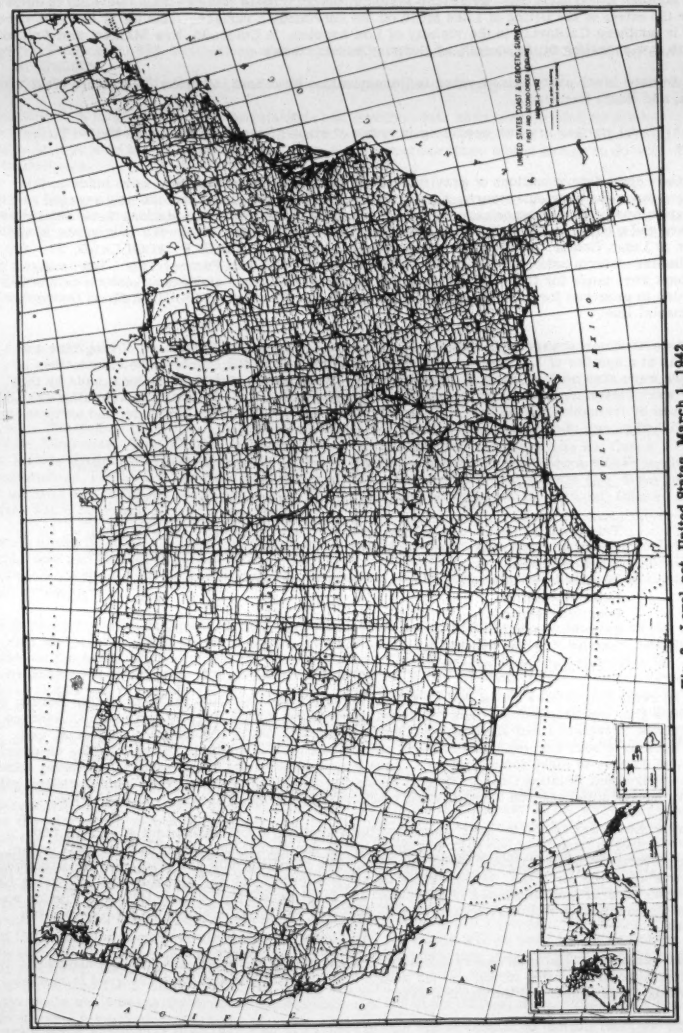

Fig. 3--Level-net, United States, March 1, 1942

Another level-party has run repeat-levels in the vicinity of Boulder Dam, Nevada, to determine the effect of the filling of Lake Mead on the surrounding surface. This party has also operated in southern California in the vicinity of Los Angeles, in Colorado, New Mexico, and Arizona, and is now operating in the vicinity of Corpus Christi, Texas.

Another level-party has operated in Pennsylvania, New York, Virginia, Maryland, West Virginia, and North Carolina.

All level-parties are now operating in areas of strategic importance to the United States Army.

Only eight determinations of gravity with the pendulum-apparatus have been made in this country since the previous report. A year ago a gravity-party of this Bureau was engaged in cooperative work in South America. A base-station and ten other gravity-stations were determined in Peru and a base-station and 12 additional stations in Colombia. This work is covered by the paper of Lieut. Comdr. ASLAKSON. In cooperation with Dr. GEORGE P. WOOLLARD, 37 gravimeter-determinations were made in Virginia, Maryland, and Pennsylvania. The isostatic reductions were made for these stations and for the South American stations. Isostatic reductions are also in progress for about 50 gravimeter-stations determined by WOOLLARD on the transcontinental line.

An astronomical party was organized in May, 1941, to make observations of longitude and azimuth at a number of Laplace stations widely scattered over the country. Determinations of latitude were also made at most of these stations. The number of determinations made by this party were eleven longitudes, two azimuths, and ten latitudes. In addition, five azimuths were determined by triangulation-parties. One astronomical station (latitude, longitude, and azimuth) was established on one of the Pacific Islands.

Table 1--Geodetic work accomplished, April 1, 1941, to February 28, 1942

Work	Completed 1941-1942	Total to date
Triangulation, first- and second-order	3,275 miles	85,275 miles
Leveling, first- and second-order	7,646 miles	292,437 miles
First-order base-lines	12	225
Second-order base-lines	1	55
Latitude-stations	10	864
Longitude-stations	11	716
Azimuth-stations	7	1,179
Gravity-stations (pendulum)	8	1,130
Gravity-stations (gravimeter)	37	37

The computing offices sponsored as Work Projects Administration projects by this Bureau in New York City and Philadelphia have continued in operation during the past year with an average employment in each of about 200 persons. Various adjustments of triangulation, traverse, and level-lines have been accomplished at these offices. At the Philadelphia Office "Tables of natural sines and cosines to eight decimal places" have been prepared and the printing is now being done at the Government Printing Office. Special tables for the computation of geographic positions with natural functions and adapted to calculating machine use have been prepared at this office.

In the New York Office we have completed the computation and adjustment of about 7,000 miles of traverse- and level-surveys accomplished in South Carolina during 1934 to 1937 under the auspices of the unemployment relief agencies. The resulting data are printed in six pamphlets which are available for issue. In this office we are now computing and adjusting and preparing for publication several thousand miles of traverse- and leveling-surveys accomplished in Florida under the Unemployment Relief Program. These data will be issued in pamphlet form during the next year.

The variation-of-latitude observatories at Gaithersburg, Maryland, and Ukiah, California, have continued in operation throughout the year. The resulting observations are used in studies concerning the movement of the Earth's axis.

The National Bureau of Standards has cooperated, as in past years, by graduating theodolite-circles and by standardizing invar-tapes for use in base-measurement and traverse-surveys.

The following publications were either printed during the year or are in press at the present time:

Special Publication 229, Deflections of the vertical in the United States (1927 datum), by J. A. DUERKSEN
Special Publication 231, Natural sines and cosines to eight decimal places

In addition, a large amount of triangulation- and leveling-data have been printed by photo-lithography. Two publications of tables of transverse Mercator projection for military mapping have also been printed by the offset process as well as numerous other tables having to do with plane coordinates.

During the coming year we expect to carry on surveys requested by the United States Army in connection with the war effort. We are making every effort to execute the necessary surveys effectively and accomplish the adjustments promptly so that these vital data may be available for Army use.

U. S. Coast and Geodetic Survey,
Washington, D. C.

REPORT ON THE PRIMARY TRIANGULATION ALONG THE NORTH SHORE OF THE GULF OF ST. LAWRENCE, 1941

Noel J. Ogilvie

One of the longest projected loops of triangulation in Canada is the network encircling the Gulf of St. Lawrence. This 1200-mile loop involves the triangulation-system along the Gaspé Coast, across Chaleur Bay, through eastern New Brunswick and Nova Scotia, across Cabot Strait to Newfoundland, northward along the west coast of this island to the Strait of Belle Isle, from the Strait of Belle Isle along the north shore of the Gulf of St. Lawrence as far as Anticosti Island, and from there southerly to the Gaspé Coast.

Most of the triangulation involved in this great loop had already been completed prior to 1941. An unfinished gap extending from a point on the north shore opposite Anticosti Island to the Strait of Belle Isle together with the northerly 100-mile portion of the Newfoundland west coast still remained uncompleted.

The project of 1941 consisted in extending the network easterly along the north coast of the gulf, from the point opposite Anticosti Island. This section of coast-line has few offshore islands suitable for the establishment of triangulation-stations. The elevation of the coastal terrain is nowhere greater than 100 feet. Ten or twelve miles inland, a line of sandy or rocky ridges rises in places to 300 feet in height. Due to the lack of topographical relief, it was necessary to make use of small geometrical figures in laying out the net. The triangle sides were limited to lengths of 8 to 18 miles and the majority of the sight-lines passed within a few feet of the ground. During sunny days, the rocks or sandy soil absorbed the Sun's heat, which would be radiated after sunset causing bad conditions of refraction.

The angular measurements were made at night using electric signal-lamps to mark the triangulation-stations. The lamps, originally designed for use on much longer lines, were too powerful for the short lines involved in this part of the net. Diaphragms of various types were used to reduce the light-beams but none of these expediencies proved satisfactory. Since the completion of the season's field-work, C. H. NEY, the officer-in-charge of this operation has designed a new duplex flash-light-type signal-lamp of small size and low battery-drain. These lamps consist of two seven-inch flash-light casings one above the other and connected in parallel to external heavy-duty batteries. Being of the fixed-focus narrow-beam type, these lamps project a powerful, concentrated ray, even when equipped with bulbs rated at 3.7 volts and 0.3 ampere. To ensure long life of filaments and to obviate any danger of burn-outs, the lamps will be used with only two batteries connected in series giving approximately three volts when new. Long tests during the past winter at Ottawa, show that this arrangement gives an intense light without any filament burn-outs. During field-operations where unattended lamps are used, the extinction of one of the duplex components would not necessarily cause a discontinuance of the observational work. The duplex lamp should provide a much-desired factor of safety against that bugbear of triangulation--the failure of unattended signal-lamps to function. During the coming season, lamps of this design will be used on the continuation of the north-shore triangulation. They should be admirably adapted to the

work as all the lamps at the rear stations are left unattended. Electric time-clocks are arranged to open and shut the circuits each night, providing for a four- or five-hour period of illumination.

The organization of the north-shore triangulation-party consisted of the engineer-in-charge, two observation-parties of four men each, three lightkeeping parties of two men each, and a station-preparation party composed of six men. For transportation along the coast, a 42-foot auxiliary ten-ton schooner was used. This transportation service was supplemented at times by power-driven fishing-boats, which were hired from local fishermen. Each party was also equipped with one or more canoes for transportation up tributary rivers.

Twenty triangulation-stations were occupied in the short field-season which obtains along this coast. Long periods of fog and gale occur at frequent intervals making work and coastwise travel impossible. Inland stations were accessible only by ascending tributary rivers. Some of these canoe-routes involved numerous portages. For example, to reach Bourque geodetic station, 12 miles inland, it was necessary to cross 22 portages in ascending a river-navigation route.

The accuracy of the season's work was well within the limits set as the standard for primary triangulation. The average triangular closure for the season was 0".82. Only three triangles showed closures greater than 2". The side equations indicate that the average corrections to the measured angles are small.

Near the village of Natashquan, a base-line was established and the base-net observed. Level stretches of terrain suitable for base-line measurements are difficult to find along the "North Shore". The rocky or sandy ridges which are numerous in most areas, are quite unsuitable for measuring operations. Most of the level terrain consists of wet muskeg partially covered with small lakes and ponds. To obtain definite information regarding the Natashquan Base-Line for the guidance of the base-measuring party, a try line was run connecting the terminal stations. The line in question, which was six miles in length, was found to cross two or three ponds. These small bodies of water will not constitute any great obstruction to measuring operations.

The north shore of the Gulf of St. Lawrence is a fisherman's paradise. The tributary rivers abound with salmon in the early summer. Fly-fishing rights for these rivers are sold at fairly high figures by the Provincial Government. Offshore along most sections of the coast, codfish, herring, and halibut are found in commercial quantities. Lobsters are also found in limited quantities in some of the bays. Wild-life is not plentiful near the coast. Of the larger quadripeds, black bear are the most numerous. Several of these animals were seen near the camps of our survey-parties during the past season.

Plant-life becomes more and more sparse as one approaches the Strait of Belle Isle. This is due to the increased severity of the climate, characterized by fog, cold winds, and low temperatures. The local fishermen, living in scattered villages in the bays and river mouths along the coast, cultivate small gardens and in some places raise a few cows. Potatoes, lettuce, onions, carrots, and a few other hardy vegetables may be grown successfully as far east as Harrington, in longitude 59° 28′. Near the coast eastward from this place the scanty tree-growth has been largely depleted, so that the local inhabitants must gain their livelihood chiefly from the sea.

Department of Mines and Resources,
Surveys and Engineering Branch,
Ottawa, Canada

PROGRESS OF GEODETIC WORK IN MEXICO

Manuel Medina

The following is a brief report on the activities of the Department of Geography of the Administration of Geography, Meteorology, and Hydrology of Mexico during the years 1940 and 1941.

This Department has received great moral and material support from the President of the Republic, General MANUEL AVILA COMANCHO, who in a letter addressed to the writer as President of the Society of Astronomical and Geophysical Studies, says in part:

> "It is my firm intention that during the following years, in so far as the conditions of the public treasury permit, that the appropriations for the Administration of Geographic Studies be improved. You may be sure that I will do everything possible so that the geodetic map of the Mexican Republic, and a good number of the geographic maps shall be completed during the years of my administration."

The proposals of the President began to be put into effect on January 1, 1941, one month after having taken over the duties of the First Magistracy, reorganizing the Administration of Geography, Meteorology, and Hydrology into three departments, (a) the Department of Geography, (b) the Meteorological Service, and (c) the Department of Hydrology. The Department of Geography has continued developing the functions inherent in the geography of the country under the plans approved by the International Congresses, that is, the formation of a map of the country on a geodetic base.

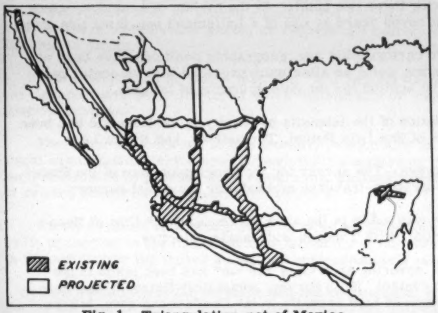

Fig. 1--Triangulation-net of Mexico

A general synopsis of the present status of Geodesy in Mexico and the accomplishments during the years 1940 and 1941 follows:

Geodetic triangulation--The sketch of Figure 1 shows the completed triangulation and that which is proposed. The completed triangulation includes that along the 98th Meridian west of Greenwich, along the Lerma and Santiago rivers, and from Los Altos, Jalisco, along the 102nd Meridian to the boundary between Zacatecas and Coahuila. It can be said that 47 per cent of the proposed triangulation has been established and that 53 per cent remains to be completed to cover the country with a geodetic net.

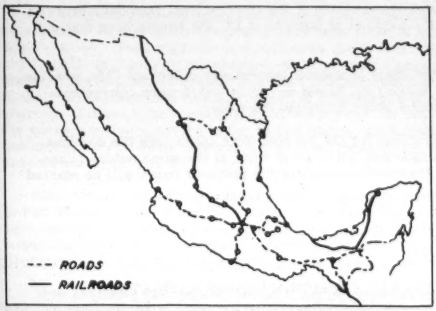

Fig. 2--Showing primary roads and principal railways in Mexico along which geodetic traverses are planned in 1942

It is planned to start the survey of large geodetic traverses this year along the primary roads and along the principal railways. The proposed traverses are shown by Figure 2.

Two local systems in Jalisco and in La Laguna, connected to the general triangulation, have been established for

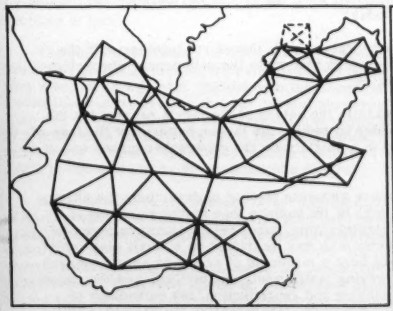

Fig. 3--Jalisco triangulation-net

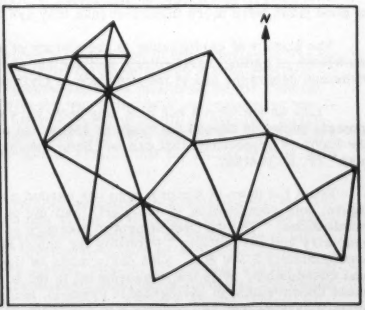

Fig. 4--La Laguna triangulation-net

immediate application to the geography of these regions (see Figs. 3 and 4).

Precise leveling for a distance of 450 km has been completed between Mexico City and the Port of Acapulco along the highway connecting these two points. In the harbor of Acapulco, mean sea-level has been observed during the last seven years by use of a Lallemand sea-level tide-gage.

Geographic astronomy--For immediate cartographic use, geographic positions have been established in the States of Zacatecas and Sonora, using an altazimuth provided with an ocular micrometer with which Talcott's method can be applied for the determination of latitude.

Gravity-measurements--The determination of the intensity of gravity in the Republic has been continued, completing a circuit in the States of San Luis Potosi, Tamaulipas, and Nuevo Leon.

Topographic and photo-topographic surveys--The survey for the geographic map of the State of Zacatecas has been completed, using topographic-traverse methods for the detail survey.

A terrestrial photo-grammetric survey was made in the area surrounding the City of Zacatecas using a Zeiss photo-theodolite, Tal-model with Topogon wide-angle objective.

An aerial survey of Guadalajara Valley, covering an area of 150 km^2 has been made in the State of Jalisco with terrestrial topographic control. This survey, completely finished, was exhibited in the Third National Geographic Congress held recently in the Guadalajara City, Jalisco.

International boundaries--The survey and demarcation of the International Boundary between Mexico and Guatemala has been continued, the parallel of latitude of 17° 49′ having been marked out on the ground for a distance of 150 km.

Local leveling in Mexico Valley--For the study of subsoil movements in Mexico City, precise levels have been established throughout the whole city, based on points which were considered stable, since they were located in the mountains which surround the valley.

Work in progress--The program of operations for the current year comprises the continuation of the geographic map of the State of Jalisco and initiation of work of the same nature in the States of Puebla and Tamaulipas. Geodetic traverse-surveys of the Mexican roads will be started in connection with this work.

Oficina de Geografía,
Tacubaya, D.F., Mexico

CARTOGRAPHY AND THE WAR EFFORT: AVIGATION VERSUS NAVIGATION

Richard M. Field

There never was a time in the history of civilization when the arts of cartography and the use of good maps were more important than they are today.

The history of cartography is the history of exploration, and, therefore, together with the knowledge of geology, archeology, and ancient and modern history is the only proper chronology of human geography and of the evolution of civilization.

"Like an ant upon a rug man may know very exactly the nature of the fabric nearby, but the general design is beyond his range of vision. In order to reduce the larger patterns of the face of the Earth to proportions that can be comprehended in a single view the geographer makes use of a map" (P. E. JAMES).

From the dawn of history, man has needed a more accurate method of describing the shape, figure, and composition of the Earth and the pattern of its surface than by the mere use of words alone. The earliest efforts to measure accurately time-space relations are in terms of geometry and cartography. Probably the oldest known map was imprinted on a small clay-tablet approximately 2,500 B.C. Such early maps as these bore a minimum of accuracy as to geographical coordinates. With the improvement in the surveying instruments and methods and the consequent improvement in cartographic symbols, map making and reproduction, the technology of modern cartography has become a highly technical profession, incorporating the scientific skills of geodesy and geophysics with those of the architect and the artist.

S. I. HAYAKAWA has said, "Words bear about the same relation to things as a map does to the territory it stands for; as a map can never tell us everything about a territory, words can never tell us everything about anything. Just as maps of maps, maps of maps of maps, etc., can be made indefinitely with or without relation to a territory, so in our thinking we can, and unfortunately do, have words about words, or reports of reports, that may or may not have any real relationship to things."

Therefore, since no single map can "tell us everything about a territory", many methods of cartography have been developed which individually or combined are particularly suited for a specific purpose.

The rapid acceleration of this geowar, particularly as it affects the United States and its national organizations which are (through their charters or their previous pronouncements) particularly interested in geodesy and cartography, emphasizes the need of most serious consideration of related research and educational methods.

First, we must take better stock of what we have done and what we have not done. As late as 1935, according to the responsible departments of our own Government, only 810,000 square miles or 26 per cent of the United States had been adequately mapped.

With the advent of the airplane and the aerocamera, mapping has been greatly accelerated during the past 20 years. Aerophotographs are not only excellent maps in themselves but also may be used to make contour or topographic maps, still the standard method of cartography for representing the physical characteristics of the surface of land. During the past few years probably over 3,000,000 aerophotographs have been taken of the United States covering over 2,000,000 square miles. The progress-map issued by the United States Department of Agriculture on January 1, 1942, is a graphic illustration of the present "portraiture" of our country. We in the United States, however, should realize that the Canadians were pioneers in the use of aerophotography due to their proper reaction to the stimulus of great areas of northern wilderness rich in mineral resources. Although their topographical survey has not yet completed as many square miles as have the corresponding agencies in the United States, the Canadian Department of Mines and Resources has an excellent control-system of filing and cataloguing which is particularly effective during the present emergency in world affairs.

Curiously enough the principal impetus to the production and use of aerophotographs in the United States has not come from its mapping agencies, such as the United States Geological Survey, but from the leading oil-companies, the United States Department of Agriculture, and the Army Engineers who, with the aid of the Army Air Corps, have made excellent use of aerophotographs in the mapping of soil-erosion, soil-conservation, and structural geology.

How available this important and valuable material may be for the principal purposes of those who are responsible in planning the coordinating activities of our people both in war and peace, is still open to question. At least we may say that no method has been available yet, so far as we know, for the full and proper use of our aerophotographs as stated above. May we hope that this situation is, in the mind of this author at least, merely a question of misinformation and not a question of fact.

The rapid development of aviation and aerophotography largely due to the stimulus of war has presented problems in research and pedagogy which are still far from solved if even realized. How many of us who have worked with the excellent topographic maps published by our Federal Geological Survey realize that the careful surveyor with the use of the best instruments of his time and at the expense of much mental and physical fatigue produces for us an accurate picture of a large area which we, without further physical labor, may gaze down upon as if we were two miles up in the air? How many teachers of aerial navigation realize that the ability to read such maps is fundamental in the training of aviators?

Not only have the techniques of aerophotography and photogrammetry revolutionized the art of cartography, but also aerial techniques have opened new vistas in the use of cartography and greatly lessened the labors and expense of accurate surveys. Of course, as in the case of the older surveying methods by transit and level, the photogrammetric method varies according to the type of terrain, distance from operating bases (landing-fields), weather-conditions, and the precision desired. Generally speaking, the present photogrammetric methods of surveying the United States cost ten per cent less than the former engineering methods. Further, we may expect immediate and continuous improvements both in aerophotography and photogrammetry. Quite recently the definition of lenses has been greatly improved and distortion minimized. The field of

coverage has been increased from 80° to approximately 93°. In the manufacture of aerial film, the discovery of new dyes which greatly increase sensitivity makes possible quicker exposure and the use of a greater variety of selective filters. This faster emulsion enables the aerophotographer to change the diaphragm to a small aperture, thus increasing the detail or definition over a wider field of the negative. A new technique for simplifying the method of assembling the mosaic and also increasing the precision and accuracy has recently been perfected. This mechanical system of triangulation when combined with accurate basic or geodetic control has greatly increased the accuracy of the "fix" for all points and thus holds the center of each print to within 0.03 inch.

We are now faced with two primary problems: (1) The lack of the proper appreciation by mathematicians and astronomers of improved techniques in geodesy, cartography, and navigation; (2) the proper effects which these techniques should have upon teaching both aerial and marine navigation, particularly to aviators. It is largely for this reason that some of us prefer to distinguish aerial navigation by the term avigation in order that we may emphasize the new and important techniques involved in the latter. While the word chart correlates naturally with the word navigation, it should be more fully appreciated that the word map correlates with those problems of avigation which involve flying over the land as well as over the oceans. The American Geophysical Union does not have to be reminded of the many interesting papers and discussions held before it on the geophysical and geodetical techniques involved in the mapping of sub-oceanic topography. Our Committee on the Geophysical and Geological Study of Oceanic Basins, together with the International Commission, the United States Coast and Geodetic Survey, the United States Navy, the British Navy, the Woods Hole Oceanographic Institute, the Scripps Institution of Oceanography at La Jolla, and others have pioneered sub-oceanic surveys, and submarine topographic maps have recently become a very important adjunct to marine navigation. Obviously, land maps which were available long before the coming of avigation should be used in helping to simplify and improve this art. It does not take very much time or preliminary training to teach our pilots and avigators how to read aerophotographs and contour topographic maps. Some of us seem to forget that we went all through this 25 years ago and that, pedagogically speaking, what we learned then should be used in the present emergency.

Every young aviator both in the present emergency and also because of the expansion of aviation in the future, should know enough about the facial expression of his own country to be able to recognize at least where he is by the distinctive peculiarities of the land which lies beneath him. Perhaps the main pedagogical difficulty in the past has been the attempt on the part of our instructors in geography and geomorphology to overemphasize the origin of land-forms and underemphasize the imitation of these forms on maps. Here again the pedagogical problem is not so much to understand how the surface of any country has come to be what it is today, but rather to be able to recognize that surface when you see it from the air, from an aerophotograph (vertical or oblique) or from a map.

This necessary simplification of the presentation of the essential requirements for effective and modern methods in avigation is not primarily a question of attempting to instruct the student in all the tools of the trade at once, but rather to be sure that he understands the problem first. Then introduce him to the essentials of the problem by the use of the most important, most effective, and simplest techniques or methods.

When an aviator by means of his compass and a good map is unable to see where he is (determine his geographic coordinates) because of "ceiling zero", then he has the opportunity, which no navigator has, of climbing to a position where by means of the celestial beacons he can continue to chart his course. This is a fundamental difference between avigation and navigation.

In conclusion:

(1) When flying over land an aviator should be able to recognize distinctive topographic features.

(2) The aviator should be able to check distinctive topographic features on either a contour-map or on aerophotographs (vertical or oblique).

(3) The present aeronautical charts of the United States (east of the Rockies) with their 1,000-foot contours are not only inadequate but dangerous, and further research is needed on how to provide aerial navigators with maps which will combine the necessary topographic information with present geodetic and geophysical controls.

(4) Under conditions of reasonably good visibility the aviator should depend primarily upon his map and his compass.

(5) For purposes of navigation, geophysical methods, such as depend upon radio beams, sonic sounders, barometers, etc., are less reliable and also afford valuable information to the enemy in time of war.

(6) Under certain night or "black-out" conditions the navigator will rely upon geophysical methods and "celestial beacons"

(7) Under conditions of "ceiling zero" the avigator may still use geophysical methods of navigation, but, if these fail or are unavailable, he may "climb" until he is able to observe the "celestial beacons" and by means of the modern instruments determine his geographic coordinates.

(8) There should be further research in the simplification of celestial navigation to produce simpler and better methods such as the use of Hydrographic Office Publication 214.

(9) In teaching map-reading and navigation it should be appreciated that to read a map, plot a course, or follow a course does not necessarily require a student to be able to make a map, or design navigation-instruments. An aviator should be able to read a contour-map or a mosaic without necessarily knowing all the techniques of photogrammetry.

(10) Through the stimulus of aviation and war, the methods of cartography and navigation have been improved and simplified, and further improvement and simplification are particularly needed, both mathematical and illustrative, for aerial navigation, that is, avigation.

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AMERICAN GEOPHYSICAL UNION

TWENTY-THIRD ANNUAL MEETING

SECTION OF SEISMOLOGY

REPORTS AND PAPERS

Washington, D. C.
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SEISMIC PROSPECTING IN NEW ENGLAND

Daniel Linehan, S.J.

The purpose of the present paper is to present, very briefly, a report on the use of seismology in geological problems in the New England Area during the past few years. The use of the seismograph in the petroleum industry is well known and the greatest advance in design of equipment and methods of operation is again almost entirely due to this industry. However, it has been too little employed in purely geological research, both because the first cost of equipment is rather high and most geological departments are too busy with their own work to devote sufficient time or resources towards maintaining a seismic field-crew and equipment.

The work in New England is divided into two general groups. The first, a study of actual ground-motion during large quarry-blasts, has been conducted chiefly by Dr. L. DON LEET of Harvard University. He has conducted experiments in all of the New England States and in eastern New York State. This work has been greatly assisted by the kind cooperation of managers and officers of quarries. These studies have not only led to integration of the earth-motion at location but has aided greatly the compilation of a set of travel-time curves and layer-depths for use in the Northeastern Area. Similar studies, also, with three-component seismometers have been made by Dr. L. B. SLICHTER in the Triassic Basin in Connecticut.

Surveys of depth to bedrock and depth of glacial and sediment cover have been made with single-component instruments and these studies make up the second group of research-projects. A combined geological and seismic survey was made of parts of the Lowell, Massachusetts, quadrangle by F. W. LEE and L. W. CURRIER under the auspices of the Massachusetts Department of Public Works and the United States Geological Survey. These men with their associates dealt especially with the section where the supposed valley of the pre-glacial Merrimac was thought to have existed. The work in that area failed to uncover any valley deep enough for such a river. It is believed that this group has surveyed other sections of New England, but the author is not acquainted with such work if it has been done.

The United States Army Engineers have likewise used the seismograph in the location of damsites in the flood-regions of the various main rivers of New England, but the data have not been made available to date.

Weston College was fortunate in receiving the loan of portable seismic apparatus from the Humble Oil and Refining Company of Houston, Texas, for geophysical research in New England. Weston College has worked in cooperation with Harvard and Yale universities, Smith College, the Geological Society of America, and various townships and individuals in Maine, New Hampshire, Massachusetts, and Connecticut. For the most part, the work was concerned with depth of cover over bedrock, but in one or two cases the structure of floored intrusives has been studied.

One problem conducted in the townships of Cochituate, Weston, Newton, Waltham, Watertown, Cambridge, and Belmont, Massachusetts, concerned the course and gradient of the pre-glacial Charles River. Surface-data from geology had presented a general idea of the river's course. The seismic surveys have verified many of the previous suppositions and has changed others and several sections have been delineated in detail. At present we have a fairly well-controlled course and determined gradient of this river. It must be remembered that in the course of such surveys only a small part of the area surveyed actually touches the river's course, and a great deal of time is spent in eliminating other sections that might be river-channels from the existing surface-data. From these surveys, some economic features have resulted that profited others. In the town of Weston, for example, structural features were encountered that might lead to a sorely needed water-supply for the town. Subsequent drilling by the Water Department verified the "hunch". Some hundreds of thousands of gallons per day may be pumped from this well, with very little "let-down". This is the only water-supply we have uncovered by the seismic method, but the local press, with a view to the sensational, has emphasized this point.

Surveys have been run in Cambridge, Massachusetts, at the region where the pre-glacial Merrimac is supposed to have met the pre-glacial Charles River. The author is not committing himself here as to whether the Merrimac did exist in pre-glacial times or not, as the region to the north has not been sufficiently studied. However, the subsurface-topography at this point differed greatly from that in other sections of the Boston Basin and could possibly lead to an inter-

pretation favorable to the junction of two great rivers. The bedrock has deep troughs, ridges, and islands that resemble the Bad Lands of the Dakotas rather than anything we might imagine around Boston. They could be meanders of the same river or the junction of several rivers. The seismic surveys were not extensive enough to determine which.

The supposed site of the pre-glacial Mystic River has been surveyed at several points in Medford, Malden, Charlestown, and Everett, Massachusetts. Points within the Medford-Malden Area appear definitely related to the original river-bed agreeing with the elevation of the pre-glacial Charles River. The region suggested in the past as the path of this river to the sea in the vicinity of Charlestown and Everett will have to be eliminated. Seismic surveys both on land and under water have shown that the bedrock is not of sufficient elevation to allow a gradient from the Medford-Malden Region to the sea.

Some work has been done by Weston College on Cape Cod in determining depth to bedrock. The surveys were preliminary and the extent of the region covered was not very great. A more complete survey is planned to take place as soon as circumstances permit.

A survey in cooperation with the Geological Society of America was made during the summer of 1941 in the Triassic formations of the Connecticut River Valley in Massachusetts. Again this survey was preliminary in character and no attempt could be made with the funds and time at the author's disposal for a continuous survey across the Valley. Certain points only could be chosen. In several of these locations, reflections from depths of several thousands of feet, believed to be the contact between the Triassics and the Paleozoic complex below, were obtained. At other points the condition of the sediments was such that shot-holes at depths of 25 feet and more were too loosely compacted to generate sufficient energy for suitable recording.

A few surveys have been carried on within the City Limits of Springfield, Massachusetts, to determine pre-glacial conditions there. An attempt was made in one or two places to find a possible ancient course of the Connecticut River, but without success; in other places the scouring effect of the glaciers on the soft sandstones especially along the erosion faces was studied.

Results obtained from the various problems have not been given in detail in this paper as they are of only local interest. The methods employed are standard and differ very little from those used in the petroleum industry and, although we have difficulties of operation such as density of population, shallow cover, high relief, etc., that the petroleum seismologist rarely encounters, there is little need of recounting them here. The variety of problems and the future of seismology as a prospecting device in New England is worthy of note. We feel, aside from the geological research ensuing from these studies, that there are many engineering problems as foundations for buildings and bridges, tunnels, damsites, etc., that could be benefited by employing seismologists to complement many of their drilling operations.

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A STATISTICAL STUDY OF THE PERIODS AND AMPLITUDES OF MICROSEISMS

James T. Wilson

It has been known for many years that the amplitude and period of the ordinary microseisms recorded at a given station vary from day to day and season to season. That the amplitude and period are greater in the winter than in the summer is also a recognized fact. However, the cause of the microseisms and the nature of their vibrations are not completely known. The present study is an attempt to obtain more information about the nature of microseismic waves.

In the early days of instrumental seismology it was concluded that microseisms were probably RAYLEIGH waves and this notion has persisted to the present. This conclusion was drawn primarily from the observation that the motion had a vertical component. It has seemed unlikely to the writer that the microseism-generating forces, whatever they may be, could set up RAYLEIGH waves without at the same time generating waves of other types.

Detailed studies by RAMIREZ [see 1 of "References" at end of paper] and KRUG [2] have shown that the microseismic movement is elliptical in both a horizontal and vertical plane. The motion in the vertical is retrograde in agreement with RAYLEIGH theory but the irregular elliptical motion in the horizontal can be explained on a RAYLEIGH-wave basis only by assuming waves

arriving from more than one direction. This assumption may be perfectly valid but it needs further verification.

LEET [2], ARCHER [4], and BYERLY and WILSON [5] have studied the phase-relationships between the various components of motion. The work of ARCHER and that of BYERLY and WILSON gave some indication that RAYLEIGH waves were present. However, the preponderance

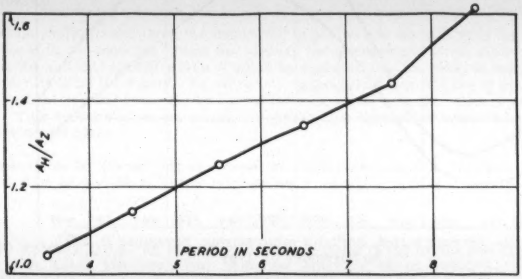

Fig. 1--Amplitude ratios, Berkeley microseisms, November 21, 1937, to November 21, 1938

of expected phase-differences was much smaller than it should have been for pure RAYLEIGH waves from one direction. Again this could be explained by assuming that the waves were arriving from several directions.

If microseisms are RAYLEIGH waves it would be expected that the ratio of the horizontal to the vertical amplitude would show a dependence on the period. The nature of the dependence would be controlled by the structure of the region. The relation between the amplitude-ratio and the period has been calculated by SUZUKI [6] and by LEE [7] for various cases.

Acknowledgment is hereby made of the assistance rendered by the personnel of the Work Projects Administration, Official Project 65-1-08-62, in securing measurements of the amplitudes and periods of microseisms recorded at Berkeley. The measurements have been made in several different ways but all of those made for the purposes of this study were of the largest amplitude and accompanying period in the ten-minute intervals centered on 8, 12, and 20 hours, Pacific standard time. The measurements were made on the three components of the Wilip-Galitzin instruments at Berkeley. These instruments have the same period and damping-factor and the horizontals have the same magnification while the vertical has a magnification of about 0.9 that of the horizontals.

The ratios of horizontal to vertical amplitude were formed by using the larger of the horizontal measurements. These ratios were then corrected for the difference in magnification between the vertical and horizontal components and tabulated according to the average period measured on the three components for that time. These data for the interval from November 21, 1937, to November 21, 1938, are summarized in Table 1.

Table 1--Amplitude-ratios of Berkeley microseisms for the interval, November 21, 1937, to November 21, 1938

Period in seconds	3-4	4-5	5-6	6-7	7-8	8-9
No. of observations	130	247	180	229	188	29
(A_h/A_z)	1.04	1.14	1.25	1.34	1.44	1.62

The average ratio of horizontal to vertical amplitude is 1.26 and the average period 5.63 seconds. The data of Table 1 are shown graphically in Figure 1. It can be seen that the ratio increases markedly with increasing period. Somewhat similar results have been shown by LEE for Uccle. However, his curve has a maximum at about six seconds and then decreases.

A comparison of the observed amplitude-ratios with those expected for the Berkeley Area

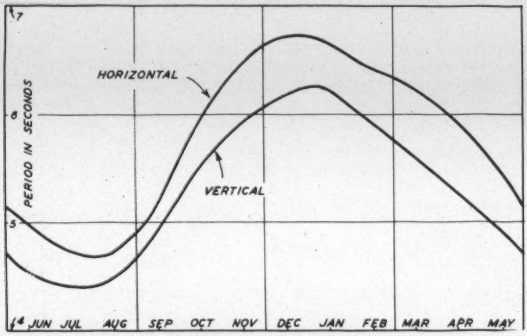

Fig. 2--Average period, Berkeley microseisms, November 21, 1937, to November 21, 1938

from the theoretical work of LEE and SUZUKI shows no agreement whatsoever. Taking the near-surface structure of the Berkeley Region to be that found by studies of the records of quarry-blasts [8] it would be expected that the ratio would increase from about 0.7 at three to four seconds to perhaps 0.9 for the longer periods.

From a study of quarry-blast records the near-surface structure in the region of Berkeley has been found to consist of a one- to two-km thick layer with a shear-wave velocity of 2.4 km/sec underlain by the normal granitic layer. To satisfactorily explain the observed ratios on the basis of the microseisms being pure RAYLEIGH waves a much thicker and much lower velocity-layer would be required. This is not compatible with either the blast-studies or the known geology of the area.

Because the amplitude-ratio data seemed to indicate that the microseisms might be a mixture of RAYLEIGH waves and some other wave-type with dominantly horizontal motion, the data were examined further. For example, the periods recorded on the horizontal and vertical components might be expected to differ by a detectable amount. The original measurements of period had been made to the nearest 0.1 sec with an error in the individual measurements of perhaps 0.2 sec. The periods measured on each component were averaged by months for the year under consideration. There were 80 to 90 measurements of period on each component each month. These data are summarized in Table 2.

Table 2--Average period of microseisms at Berkeley

Date	Component		
	Z	N	E
1937-38	sec	sec	sec
Nov. 21-Dec. 21	6.04	6.81	6.73
Dec. 21-Jan. 21	6.71	7.02	6.93
Jan. 21-Feb. 21	5.54	6.00	6.08
Feb. 21-Mar. 21	6.06	6.79	6.63
Mar. 21-Apr. 21	5.00	5.56	5.77
Apr. 21-May 21	5.35	5.85	6.03
May 21-June 21	4.26	4.72	4.72
June 21-July 21	4.53	4.90	4.84
July 21-Aug. 21	4.37	4.65	4.61
Aug. 21-Sep. 21	4.43	4.63	4.65
Sep. 21-Oct. 21	5.78	6.11	6.16
Oct. 21-Nov. 21	5.72	6.37	6.31
Grand averages	5.32	5.78	5.79

The data of Table 2 are shown by smoothed curves in Figure 2. The difference in period recorded on the vertical and on the horizontals is striking. It amounts to almost half a second on the average and is remarkably consistent throughout the year. The very close agreement between the average periods on the horizontals argues against errors in measurement by the observer and remeasurement by the writer verifies this. No records have been examined other than those from Berkeley but it seems unlikely that this is due to any instrumental peculiarity. However, this requires verification.

One obvious explanation of both the difference in period and the failure of the amplitude-ratios to agree with the expected values has already been suggested. If the microseisms are a mixture of LOVE and RAYLEIGH waves it would be expected that the ratio of horizontal to vertical amplitude would be increased. Furthermore, if the LOVE waves were of slightly longer period the apparent periods recorded by the horizontals would be longer than those recorded on the vertical. This mixture of waves would, of course, also explain the observed elliptical vibration in the horizontal plane.

This explanation is offered only as a tentative explanation and it is realized that much further work must be done before the nature of microseismic vibration is fully understood.

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PROGRESS-REPORT ON SEISMOLOGICAL ACTIVITIES OF THE UNITED STATES COAST AND GEODETIC SURVEY, APRIL 1, 1941, TO MARCH 31, 1942

Frank Neumann

Teleseismic work--This was maintained with few exceptions on the same basis as in the previous year. (1) The privately operated station of Mrs. M. M. SEEBERGER at Des Moines, Iowa, resumed routine recording early in 1942. The records are being forwarded to the Coast and Geodetic Survey. (2) A McCOMB-ROMBERG seismograph was installed at the Spring Hill (Alabama) Seismograph-Station through the cooperation of The Franklin Institute and the Coast and Geodetic Survey. (3) WENNER seismometers for the Sitka Observatory were equipped with new coils, dynamic testers, and metal covers which can be oil-sealed; a one-component temporary instrument was in operation at the station during the alterations and a new recorder equipped with a WALLACE and TIERNAN motor modified for accurate control by a pendulum clock was placed in operation. (4) There was some cooperation with the National Park Service in connection with the establishment of a new station at Flagstaff, Arizona. (5) In cooperation with the International Seismological Association, photographic paper and paper for mechanical seismographs were supplied for the Danish stations at Ivigtut and Scoresby Sund, Greenland. (6) Four seismographs are now being operated in the Boulder Dam Area, one having been added in 1941; new stations are being established in the vicinities of Grand Coulee Dam and Shasta Dam; these projects are being conducted jointly with the Bureau of Reclamation and with the cooperation of the National Park Service.

The Washington and Philadelphia Work Projects Administration offices of the Coast and Geodetic Survey processed records for 22 stations and published the results for 24. Reports were issued through April, 1940, and are completed in part through November, 1940. In the Washington office approximately 40 preliminary determination-of-epicenter cards were issued on the basis of data received through Science Service, the Jesuit Seismological Association, and other cooperating organizations. In recent months the curtailment of Government radio facilities has forced outlying stations to limit the sending of earthquake-messages to those covering major shocks only.

The program for collection of felt-earthquake reports along the Pacific Coast and in the western mountain region was continued under the Seismological Field Survey Office with the cooperation of many organizations and individuals. The University of California and the Seismological Laboratory of the California Institute of Technology were especially active in California. State collaborators outside of California supervise the collection of information within their respective States. The following is a list of the collaborators:

ARIZONA--Dean G. M. Butler, University of Arizona, Tucson, Arizona
COLORADO--Professor C. A. Heiland, Colorado School of Mines, Golden, Colorado
IDAHO--Professor Vernon E. Scheid, University of Idaho, Moscow, Idaho
MONTANA--Dr. Francis A. Thompson, Montana School of Mines, Butte, Montana
NEVADA--Professor Vincent P. Gianella, University of Nevada, Reno, Nevada
NEW MEXICO--Professor Stuart A. Northrop, University of New Mexico
OREGON--Dean E. L. Packard, Oregon State Agricultural College, Corvallis, Oregon
UTAH--Professor J. Stewart Williams, State Agricultural College, Logan, Utah
WASHINGTON--Dr. Harold E. Culver, Washington State College, Pullman, Washington
WYOMING--Professor Horace D. Thomas, University of Wyoming, Laramie, Wyoming

In the rest of the country there was no earthquake important enough to justify the issuance of a special report.

"Principles underlying the interpretation of seismograms" was reissued in a slightly modified form and with new travel-time tables attached. In view of the steady demand, work will begin on a complete revision during the present year with a view to making it available in the form of a publication.

Strong-motion work--The strong-motion program was continued on the West Coast and in the western mountain region. Records were obtained for nine earthquakes. About 50 records in all were obtained. The strongest shock was that at Eureka on June 30, 1941, the epicenter being offshore.

The six-inch accelerograph-recorders were being changed to 12-inch as time and funds permitted. Sensitivity of a number of the accelerographs was reduced by optical methods. Sensitivity of one instrument was reduced by shortening the pendulum-period to 0.07 second in lieu of the standard 0.10 second. Should this latter method prove satisfactory, it will have the advantage of giving true acceleration-values for lower-frequency vibrations than was previously possible.

Development of the multipendulum-vibration analyzer was continued in the San Francisco office.

A special report on the analysis of the accelerogram for the Imperial Valley Earthquake of May 18, 1940, was issued in lithographed form. This is the first analysis in which ground-motion has been discussed in terms of longitudinal, transverse, and rotational motion, and period-data have been presented in the form of envelopes.

Redetermination of displacement from the accelerograms of the Helena 1935 Earthquake was undertaken in view of the unsatisfactory character of the computation of 1935. The features of the revision are a six-cm range of motion on the east-west component and strong evidence of a permanent displacement of about two cm coincident with the maximum velocity-wave.

Processing of the accelerogram of the Vernon 1933 Long Beach Earthquake revealed displacements in the longer-period range slightly greater than those computed for the Los Angeles Subway Terminal Station. The recorded short-period accelerations, however, are several times greater at Vernon, which is on Los Angeles River alluvium, than at the Terminal Station, which is on rock.

U. S. Coast and Geodetic Survey,
Washington, D. C.

ON THE DETERMINATION OF ELASTIC CONSTANTS WITHIN THE EARTH FROM SEISMOMETRIC DATA

Archie Blake

(Abstract)

In the absence of data good enough to permit the method of PEKERIS and SLICHTER to be used, the most informative source of knowledge concerning the elastic constants within the Earth is the travel-time curves of the seismic P- and S-waves. The computation of the velocity-function from the travel-time curve involves the solution of ABEL'S well-known integral equation. The treatment of this type of equation is facilitated on the theoretical side by the terminology of functions as opposed to variables, and on the computational side by central difference methods and the use of machines.

Washington, D. C.

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AMERICAN GEOPHYSICAL UNION

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THE STRUCTURE OF THE WIND OVER A SAND-DUNE

H. Landsberg

In October, 1941, members of the Institute of Meteorology of the University of Chicago and the Geology Department of the University of Michigan made a joint field-trip to study the aerodynamic properties of sand-dunes on the east shore of Lake Michigan. A preliminary report on some of the results follows.

The vertical and horizontal wind-distribution over a small but typical dune near Stevensville, Michigan was studied. It was a so-called blow-out that had been cut through an older chain of grown-over dunes. The instruments used for the wind-measurements were BIRAM-type anemometers. Figure 1 shows lines of equal wind-velocity expressed in per cent of the value measured at a reference-station located in the neck of the blow-out. There the dune has been cut about 100 feet below the level of the grown-over portions of the dune. The blow-out forms a fairly narrow channel there, about 75 feet wide.

The longitudinal cross-section of the dune shows the customary eddy behind the back slope and also another eddy behind a shallow fore-dune. It is possible that this fore-dune owes its existence to an original windward eddy. This eddy will prevent the transport of sand from a given area, which will result in the formation of a terrace. The terrace will intensity the eddy and that

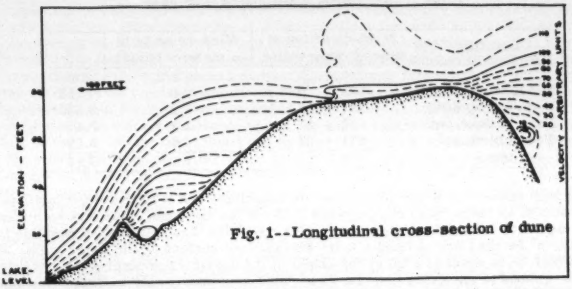

Fig. 1--Longitudinal cross-section of dune

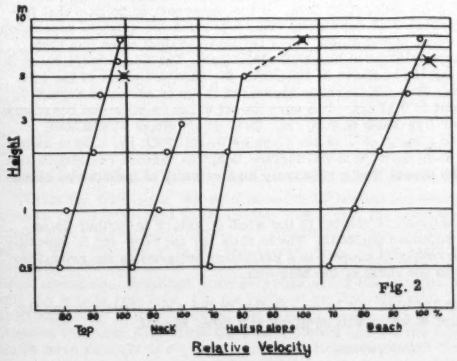

Fig. 2

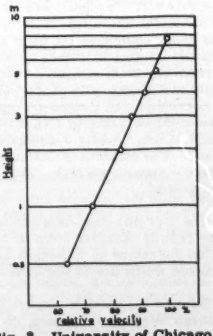

Fig. 3--University of Chicago baseball court

may lead to the piling up of the fore-dune.

On the front slope, in the neck and on the top of the dune, the most important feature is the high velocity near the ground. Most irregular is the vertical distribution of wind-velocity in the neck. This is due to a BERNOULLI effect produced by the narrow passage between the two dune-ridges on either side of the blow-out.

Besides for the study of streamlines, the vertical wind-profiles can be used to obtain information on the roughness of the terrain. At four points reasonably good profiles were obtained that could be used for the purpose of determining the roughness-coefficient Z_0 that appears in PRANDTL'S relation for wind-distribution near the ground

$$u_Z = 2.5 \sqrt{\tau/\rho} \log_e (Z/Z_0)$$

where u_Z = wind-velocity in height, τ = shear stress, and ρ = density of air. The profiles of wind obtained are shown in Figure 2. The best of all the curves is the one taken near the beach with four points falling on a straight line and only one point appreciably off the line. Half-way up the slope and on the top of the dune there are considerable discrepancies above five meters high. In the neck of the dune only the lowest three meters shows an approximately logarithmic wind-distribution. There the BERNOULLI effect is most pronounced and the logarithmic law does not hold under most circumstances. Table 1 gives the calculated roughness-coefficients for the various points.

Table 1--Roughness-coefficients over dune

Locality	Wind-direction at time of observation	Wind-velocity in a meter's height	Z_0
	°	m/sec	cm
Beach	225 ± 5	2.8	0.155
Half-way up dune	270 ± 15	1.9	0.125
Neck of blow-out	90 ± 25	3.8	0.14
Top of blow-out	315 ± 35	4.2	0.09
Mean	....	....	0.13

All of the four values are of the same order of magnitude and it is therefore justified to average them and accept as mean value of roughness 0.13 cm for the dune. There is an indication that roughness at the beach is slightly higher than on the top of the dune. It is very possible that the modeling action of the wind has created a more streamlined surface at the latter point. PRANDTL has suggested that Z_0 is equal to 1/30 of the height of the obstacles producing the roughness. This would correspond to obstacles four cm high. This is probably only an order of magnitude, since PRANDTL'S figure was obtained from laboratory data. It has, however, to be said that the only obstacles are a few little lumps produced by dead wood and roots from the original vegetation of the dune, otherwise the dune has become streamlined. This becomes evident when one compares the roughness values obtained here with those obtained elsewhere. The next lowest value is one resulting from measurements during the summer of 1941 over the baseball court of the University of Chicago with short-cut grass. The wind-profile measured there is shown in Figure 3. The corresponding roughness coefficient is 0.22 cm. The next lowest value found in the literature is one communicated by SVERDRUP for firn-snow of 0.25 cm. Over short grass SVERDRUP found 0.54 cm, closely corresponding to a value of 0.49 cm given by PAESCHKE for a level snow-surface. The continuous action of the wind upon the dune-surface is apt to remove resistance and produce a smooth surface. This in turn means that a relatively high velocity is maintained close to the ground.

The fact that dune-morphology is intimately related to the wind-structure is further borne out by results obtained from drift and balanced balloons. These show for the blow-out in question that the curvature in its length axis corresponds closely to a deflection suffered by the prevailing southwest winds due to the dune-chain to the north of the blow-out.

Data on the sand-transport through the blow-out in its relation to the wind-structure and the gustiness were also obtained, an account of which will be given at a later instant.

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NOCTURNAL WIND-VELOCITY, EDDY-STABILITY, AND EDDY-DIFFUSIVITY ABOVE A CITRUS ORCHARD

R. A. Kepner, L. M. K. Boelter, and F. A. Brooks

Introduction--The results discussed in this paper were obtained at the Citrus Experiment Station of the University of California at Riverside during the winter of 1938-39, as part of the research-project on heating of orchards. The observations were made in and above an orange-orchard in which the spacing of trees was 20 feet by 24 feet. The average size of the trees was about 11 feet high by 11 feet in diameter. The observation-station was located on terrain which slopes gradually from the foot of a range of hills located about a mile to the east. At the point of observation, the slope is about 1-1/4 feet per 100 feet. For the most part, observations were made only during nights when there was a definite inversion and relatively low wind-velocities, as the resulting steady conditions were essential for the orchard-heating studies. The prevailing direction of the surface-winds was from the southeast, down the natural slope.

Vertical distributions of wind-velocity were obtained in conjunction with measurements of temperature and humidity. (Measurements of wind-velocity were made with a six-inch Biram-type vane-anemometer No. 5967 by Keuffel and Esser, which is reasonably accurate to velocities as low as one-half mile per hour. The anemometer and a tail were mounted on a vertical shaft with ball-bearing supports so that the anemometer automatically faced directly into the wind. By means of cables, running over pulleys supported by a cross-wire between the tops of two 60-foot poles, the anemometer and thermocouple assembly could be set at any height between 4 feet and 50 feet. Electric contacts were installed on one of the gears inside the anemometer so that for every 12.5 feet of wind a contact was closed and an impulse given to a magnet which moved a pen laterally on the chart of a time-recorder. The values of wind-velocity were obtained from the chart by counting the number of impulses recorded by the pen per unit of time.) The anemometer and thermocouple assembly were raised to various heights in succession up to 50 feet, holding at each height for one to two minutes. This interval was determined by the time required to obtain readings of the temperature and the wet-bulb depression as indicated by thermocouples. The entire traverse usually required about 15 minutes. Since readings at different elevations could not be made simultaneously, this method introduces the possibility of error due to changes in air-conditions during the time required for the traverse. However, by averaging a number of traverses together, variations due to time-differences become relatively unimportant. (In order to make all observations simultaneously during the two following winters, three anemometers were placed at fixed elevations above the tree-tops of 50 feet, 30 feet, and 20 feet. Velocities were recorded continuously from each of these instruments. However, preliminary analysis of these data indicate some discrepancy that is partly due to the use of three different anemometers of two different makes, although all were calibrated. Conditions were not steady enough to determine velocity-profiles from measurements at only three elevations above the tree-tops without knowing typical distributions from previous determinations at many levels. The availability of anemometers and recording apparatus was a practical limitation to the number of elevations at which velocities could be recorded simultaneously. The results included herein are all based on the data obtained by moving the same anemometer from one height to the next.)

Within the tree-zone, the velocities for individual traverses were often so small as to be below the range of the vane-type anemometer, and in fact the anemometer-wheel often did not even rotate at these lower elevations. Hence, for velocities in this region, the results of observations with four hot-wire anemometers in 1940-41 are used. These anemometers were placed at 0.5-, 2-, 5-, and 8-foot elevations at the center of a tree-space, and there was also a vane-anemometer at 20-foot elevation. Readings were recorded every ten minutes during six nights, giving a total of about 175 sets of readings. On the basis of the five-foot velocity, these readings were segregated into groups of 10 to 30 sets each, and averages were obtained for each such group. The velocities at each of the other elevations were then plotted against the velocity at five-foot elevation. The results were straight lines, which did not quite pass through the origin. From these curves, values for a vertical profile could be obtained for any particular value of the velocity at 20-foot elevation.

Analytical considerations for velocity-profile--Before discussing the results of the wind-observations made at Riverside, reference should be made to some of the analytical treatments which have previously been published [see 1, 2, 3 of "References" at end of paper]. SVERDRUP gives a résumé of the subject citing the logarithmic distribution of velocity for indifferent stability (see Appendix I). However, when the air is convectively stable, SVERDRUP uses a power-function for interpreting the variation of wind-velocity with height. This is in the form, after amplifying SVERDRUP'S equation (33) to include z_r

$$U = U_1 \left(\frac{z + z_r}{z_1 + z_r}\right)^{(1+\text{[illegible]})/4n}$$

where U is the velocity at elevation z, z_r is a roughness parameter, and n is a constant whose value depends on the roughness of the boundary-surface and upon the flow-conditions. From wind-tunnel experiments of air-flow over flat plates, n would be expected to increase with velocity, but should be smaller if the surface is rough, other conditions being equal. In this case z_r is the vertical distance from the real surface to that level at which the velocity, U, would be zero when extrapolated downward according to the power-law. SVERDRUP shows that if the temperature- and velocity-distributions are similar, n has a value of 3, and

$$U = U_1 \left(\frac{z + z_r}{z_1 + z_r}\right)^{1/3}$$

Near similarity of temperature- and velocity-profiles above orange-trees is shown in Figure 4.

The data upon which the following analysis is based were obtained at night when there was definite temperature-inversion, resulting in atmospheric stability. Hence the power-law was used as a basis for analysis of the data. Attempts to apply the logarithmic law showed that it could not be made to represent the data as closely as the power-law.

In the above equation, z must be measured from a plane at the top of the rough surface if z_r is to be positive. In the case of an orchard, the top of the rough surface is at the tree-tops. Since the height of the tree-tops is not well defined, z in the following analysis is measured with respect to the ground-surface, and a value of z'_r is subtracted from the height above ground. Then the roughness-parameter with respect to the tree-top elevation is $z_r = [(\text{tree-height}) - z'_r]$, and using a constant c instead of $[U_1/(z_1 - z'_r)^m]$, we may write

$$U = c\,(z - z'_r)^m$$

The analysis of data includes the determination of the constants c, m, and z'_r for various conditions, as well as the evaluation of RICHARDSON'S criterion for eddy-stability, and of eddy-diffusivity for several combinations of velocity and temperature-inversion.

Relation of wind-velocity to height--A total of about 135 velocity-traverses were made during 30 nights, with temperature-inversions ranging from 3° to 20°F. All values of inversion referred to in this report are the temperature-differences between the 5-foot and the 60-foot elevations. The velocity-traverses were divided into five groups according to the 50-foot velocity, with each group containing about 25 traverses. Table 1 gives the average velocities at eight elevations above the tree-tops for each group. Each velocity-group was further subdivided into three inversion-groups whose average inversions were 5°, 10°, and 15°F.

The value of z'_r was determined for each of these subdivisions by plotting the velocity (average for the subdivision) against height $(z - z'_r)$ on log-log paper. In each case, several values of z'_r were tried. The value resulting in the best straight line was taken as z'_r for that particular inversion and velocity-group. Table 2 shows the values obtained for z'_r. For reasons which will be discussed later, the two lower velocity-groups could not be made to fit the power-law above 25-foot elevation. Hence it was difficult to determine definite values of z'_r for them. Although there is a wide variation in the z'_r-values for different inversions and velocity-groups, there is no indication of any definite relation between z'_r and inversion or velocity. However, each value of z'_r in Table 2 is based on the average of only 6 to 12 traverses; hence it should not be concluded that no such relation exists.

Since no definite correlation between z'_r and inversion or velocity was evident, a constant

Table 1--Average wind-velocities at various heights (mph)
(Inversion-range, 5°-15°F)

Velocity-group	Heights above ground, z, feet											
	Hot-wires, 1940-41				Vane-type anemometer							
	0.5	2	5	8	11.5	14	19	24	29	34	41.5	50
I	0.40	0.40	0.40	0.50	0.72	0.87	1.16	1.54	1.47	1.37	1.53	1.48
II	0.63	0.71	0.69	0.84	1.00	1.38	1.96	2.09	2.27	2.26	2.33	2.32
III	0.70	0.81	0.78	0.94	1.09	1.47	2.15	2.28	2.55	2.85	2.96	3.04
IV	0.85	1.01	0.96	1.15	1.34	1.61	2.44	2.95	3.26	3.44	3.59	4.07
V	1.41	1.78	1.63	1.93	2.22	2.67	3.76	4.85	5.23	5.83	6.31	7.21

Table 2--Values of z'_r (feet)

Velocity-group	5°-inversion		10°-inversion		15°-inversion	
	Velocity at 20-foot elevation, mph	z'_r, feet	Velocity at 20-foot elevation, mph	z'_r, feet	Velocity at 20-foot elevation, mph	z'_r, feet
I	1.3	...	1.2	...	1.2	...
II	1.6	...	1.9	...	2.0	...
III	2.0	6	2.1	13	2.3	10
IV	2.3	6	2.5	11	2.6	13
V	5.1	13	3.5	8	3.1	4

value of z'_r was chosen and the average velocities for each velocity-group (including all inversions) were plotted. The average value of z'_r from Table 2 is 9.3 feet. Hence the velocity-data were plotted, first using z'_r = 10 feet and then with z'_r = 9 feet. The ten-foot value (Fig. 1) resulted in better fits to straight lines on log-log paper, and therefore is considered to be the proper z'_r for this orchard. If we take the tree-height to be 11 to 12 feet, z_r with respect to the tree-tops is one to two feet, roughly between 10 and 20 per cent of tree-depth.

Calculations from data submitted by W. L. FONS [4] to L. M. K. BOELTER give z_r = 0.3 foot for uniform brush three feet high; and z_r = 0.06 foot for open, bare-surface country. In FONS' data, z_r is about ten per cent of the depth of the cover. Hence, considering that the level of the tree-tops in the orchard is indefinite and irregular and that there are channels through the tree-zone, the value of one foot to two feet for z_r is not unreasonable. Observations close to the ground over mowed grass one cm high by A. C. BEST [5], during an inversion of 1°F per meter, cannot be represented accurately by the power-law. However, if one neglects the two end-readings (for 2.5-cm and 200-cm heights), the remaining five values will lie very close to a straight line on log-log plotting if three cm is subtracted from the given heights. It is to be noted that BEST'S observations are well represented logarithmically (see Appendix I).

It will be noted that in Figure 1 the straight lines for the three lower velocity-groups are parallel (indicating the same value of exponent m for each), while the lines for Groups IV and V converge slightly toward the others as the height is decreased. Groups I and II, however, fit the straight lines only between the heights of the tree-tops and 25 feet ($z - z'_r$ = 1 foot to 15 feet). Above 25 feet the actual velocities are less than would be expected from the power-law, and, in fact, become practically constant above 35 feet. A plausible explanation of this deviation is that for very low velocities, the motivating force is gravitational in the flow of cold air down the slope, with the quiet, warmer air overhead causing a drag on the top surface of the layer of cold air. In the case of greater velocities, there is a greater depth of movement of overhead air. During the four winters of orchart-heating studies, it has repeatedly been observed that whenever the wind-velocity at the 20-foot elevation exceeded about 2-1/2 miles per hour for any length of time, the temperature-inversion was reduced or destroyed. The curves of Figure 1 indicate that the change in type of air-flow (between Groups II and III)occurs when the 20-foot velocity is about two miles per hour. Thus, it would seem that, at least for this particular location at Riverside, the temperature-inversion is affected whenever the overhead air-movement predominates over the surface-drainage of cold air.

Values of the constants c and m in the power-law are shown in Figure 2 as functions of the 20-foot velocity. The values of m are the reciprocals of the slopes of the lines in Figure 1, while c is the velocity-value at $(z - z'_r) = 1.00$ (that is, at $\log [z - z'_r] = 0$). In other words,

$\log U = m \log (z - z'_T) + \log c$. Below two to three miles per hour (at 20-foot elevation), m has a value of 0.32, which compares with the exponent of 1/3 arrived at by SVERDRUP on the basis of similarity of temperature- and velocity-distributions. (The average wind-profile of Groups III and IV is plotted in Figure 4 to arbitrary abscissa-scale which shows the similarity above the tree-tops with an average temperature-profile observed under stable conditions at Riverside. The velocity-scale was chosen to bring the two profiles together at 14 and 50 feet.) Theoretically, as the velocity at a given height increases (which decreases the stability), n should increase, and the exponent $[(1 + n)/4n]$ in SVERDRUP'S power-equation should decrease. Figure 2 indicates a slight increase of m with velocity for the modified power-law containing z_T as a roughness-factor. Possibly the value of m should be considered as constant over the range of velocities encountered, but data obtained by FONS [4] over open, level country, also indicate a slight increase of the exponent when the velocity increases, in the range from five to ten miles per hour at 20-foot elevation.

The relation of wind-velocity to height is more readily visualized if plotted on cartesian coordinates. This is done in Figure 3 for each of the five velocity-groups. The solid lines with dashed extensions represent the power-functions determined from Figure 1. The solid extensions departing from the power-law curves were drawn to fit the data in the regions where the power-law does not hold. Within the tree-zone, the profiles were obtained by using the hot-wire-anemometer velocities corresponding to the 20-foot velocity for each of the five velocity-groups (Table 1). Each of these hot-wire values was read from a curve based on about 175 readings, as discussed in the introduction.

Atmospheric eddy-stability--The application of the power-law to velocity-distribution in preference to the logarithmic law depends partly upon the condition of stability. Stability has a dual meaning: (1) That concerning lapse-rate, that is, whether the potential temperature increases or decreases with elevation; (2) that concerning eddy-turbulence, that is, whether eddies (due to wind-shear) tend to persist or to die out. The first interpretation of lapse-rate in relation to adiabatic expansion is well known. The second interpretation, for eddy-decay, has been deduced by RICHARDSON [6] (for abstract see Appendix II). RICHARDSON'S criterion for stability is referred to by LETTAU [7] as RICHARDSON'S number, Ri, and is dimensionless. For the specific case of the atmosphere, this criterion (not directly applicable to cold-air flow) is expressed as

$$Ri = \frac{g}{T}\left[\frac{dT}{dz} - \left(\frac{dT}{dz}\right)_{adiabatic}\right] \Big/ \left(\frac{du}{dz}\right)^2$$

where (du/dz) is the vertical gradient of wind-velocity in (ft/sec) per foot; g = gravitational constant, 32 ft/sec^2; and T = absolute temperature, °Rankine; $(dT/dz)_{adiabatic}$ has a value of -5.5 F per

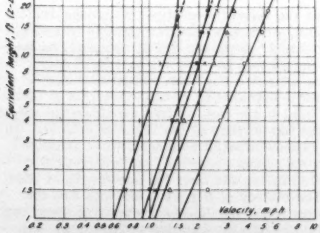

Fig. 1--Relation of wind-velocity to equivalent height above smooth plane surface [Equivalent height = (actual height) - 10 feet; each velocity-curve includes inversions ranging from 5°-15° F; average inversion = 10° F between 5-foot and 50-foot elevation]

Values of k and m in the equation, $u = c(z-z'_T)^m$ $(z'_T = 10 \text{ ft})$

Velocity group	Vel. at 20 ft. elev., m.p.h.	c	m
I	1.25	0.60	0.32
II	1.9	0.89	0.32
III	2.1	0.99	0.32
IV	2.5	1.07	0.36
V	4.0	1.90	0.43

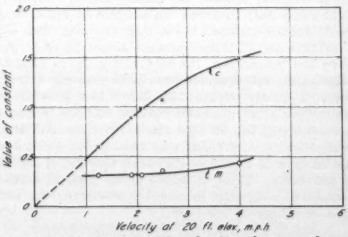

Fig. 2--Variation with velocity of power-law constants for interpreting velocity-profile above an orange orchard during nocturnal inversions

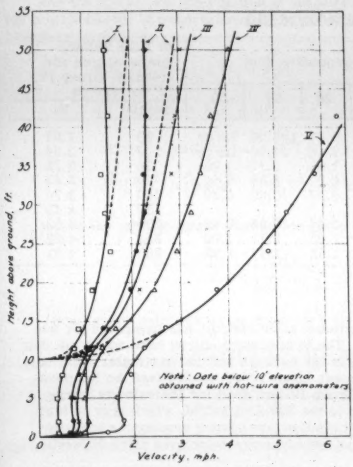

Fig. 3--Relation of wind-velocity to elevation for various magnitudes of velocity

1000 feet. When Ri = 0, that is, $(dT/dz) = (dT/dz)_{adiabatic}$, the condition is known as indifferent (convective) equilibrium [3]. A negative value of Ri signifies convective instability, while the positive value indicates a convectively stable atmosphere. RICHARDSON shows that eddies will just die away when $(du/dz)^2 = (g/T)[(dT/dz) - (dT_A/dz)]$. Hence Ri = 1 for this critical condition for decay of turbulence. SVERDRUP [3] speaks of the condition Ri > 1 as "great stability." Thus when there is great stability there is a tendency toward both thermal stratification and dying out of turbulence.

In evaluating RICHARDSON'S modulus for various conditions, the velocity- and temperature-distributions with elevation must both be known. Typical nocturnal temperature-profiles are shown in Figure 4, for 5°, 10°, and 15° F inversions. These curves are based upon many temperature-profiles obtained at Riverside during the orchard-heating studies. The average of the inversions for all of the wind-traverses was about 10° F. Hence RICHARDSON'S numbers were computed at various heights for each velocity-group, using the 10° curve of Figure 4. With velocity Group IV, the 5° and 15° inversion-curves were also used to demonstrate the effect of inversion on stability.

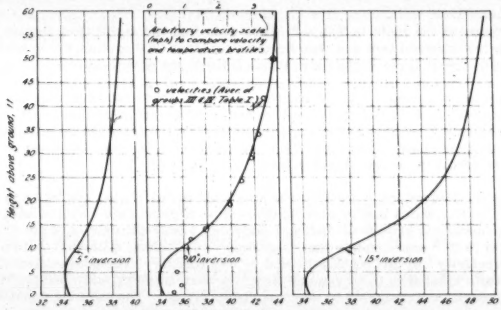
Height above ground, ft.
Arbitrary velocity scale (mph) to compare velocity and temperature profiles
velocities (Aver. of groups III & IV, Table I)
5° inversion
10° inversion
15° inversion
Temperature, °F

Fig. 4--Typical inversion-curves at Riverside for various amounts of inversion (in orange orchard with trees 11 feet high)

In the equation for Ri, an average value of T was taken as 500° Abs. (40° F). Values of (dT/dz) and (du/dz) at various heights were obtained by measuring the slopes of the curves in Figures 3 and 4, and multiplying by a scale-factor. If α is $\tan^{-1}$ of the slope at any point, then for Figure 3 (du/dz) = 0.245 cot α in ft/sec per ft, and for Figure 4 (dT/dz) = 0.400 cot α in °F/ft.

Table 3 contains the results of the calculations of Ri. It will be noted that the least stability in all cases, according to RICHARDSON'S criterion, occurs at about 12- to 15-foot elevation, which is just above the tree-tops. This was not expected and is probably due to neglecting density-pressure gradients. All stability-factors given in Table 3 are positive because there was always temperature-inversion during these observations. For some of the conditions included in the Table, it appears that the stability-criterion is a maximum at 30 feet. However, the decrease in Ri between 30 feet and 50 feet is probably due to the variations in slope possible in drawing the top portions

Table 3--Richardson's modulus (Ri)

Velocity group	Velocity at 20-foot elevation, mph	°F-inversion, 5 to 60 feet	Heights above ground, z, feet						Ri from balloon temperatures and velocity; Group IV, 12°-inversion	
			10	12.5	15	20	30	50	Height	Ri
I	1.25	10	4.72	1.14	2.61	5.41	135.00	large	20	1.97
II	1.9	10	3.07	0.72	1.14	2.18	24.00	large	30	2.84
III	2.1	10	3.07	0.72	0.92	1.85	2.71	1.90	50	3.32
IV	2.5	10	4.05	0.66	0.53	0.97	1.36	0.96	70	3.48
V	4.0	10	1.34	0.51	0.17	0.27	0.35	0.28	100	3.74
									150	4.43
IV	2.5	5	1.78	0.30	0.26	0.46	0.63	0.59	200	4.53
IV	2.5	10	3.07	0.72	0.92	1.85	2.71	1.90	250	4.32
IV	2.5	15	4.65	1.04	0.98	1.62	1.47	1.22	300	4.31

of the temperature-inversion curves.

In further investigation of the possibility of a maximum at 30 feet, Ri was computed for one particular case at different elevations up to 300 feet. The temperature-curve used was from data obtained with a thermocouple on a captive balloon, and is the average for one particular night only. On this night, the inversion between 5 feet and 60 feet was about 12°F. At 300 feet the temperature was changing very little with increased height. Group IV was used for the velocity-curve, and it was assumed that the power-law would apply up to the 300-foot height, which may or may not be true. However, this assumption of velocity-distribution furnishes a reasonable basis to give some indication of relative values of Ri. Values of (du/dz) were calculated after differentiating the equation $U = c\,(z - z'_r)^m$ to get

$$(dU/dz) = cm\,(z - z'_r)^{m-1}$$

The results are shown at the right in Table 3. It is seen that the stability-criterion would increase up to a height of a few hundred feet and then become constant or diminish if one may assume that the velocity-distribution at these higher elevations follows the power-law.

With the exception of Group V and the narrow zone just above the tree-tops for the other Groups, the condition of great stability (Ri > 1) prevails when the inversion is 10° or more. Thus, the use of the power-law in preference to the logarithmic law is justified in so far as considerations of stability are concerned. The stability at 15° inversion is about the same as at 10°, while at 5° inversion, the stability is considerably less.

Eddy-diffusivity--The velocity-distribution above the orchard also can be used to compute the values of eddy-diffusivity which can be used to determine approximate rates of heat-transfer, when there is no pronounced growth or decay of eddying. [Eddy-diffusivity, ϵ (in ft^2/sec) times mass-density, ρ (in lb ft^{-4} sec^2) equals the "austauch" coefficient, η (in lb ft^{-2} sec), which is called "eddy-convectivity" by RICHARDSON and by SVERDRUP. The eddy-diffusivity, ϵ, corresponds to kinematic viscosity, ν, in viscous flow. In heat-transfer, eddy-diffusivity times volumetric heat-capacity corresponds to thermal conductivity.] The defining equations are

$$(\tau/\rho) = \epsilon\,(dU/dz)$$

$$(\tau/\rho) = \ell^2\,|\,dU/dz|\,(dU/dz)$$

$$\ell = \kappa\,|(dU/dz)/(d^2U/dz^2)|$$

} For uniform distribution of pressure-gradient; that is, not directly applicable to density-currents

Hence $\epsilon = \ell^2\,|dU/dz| = \kappa^2\,[(dU/dz)^3/(d^2U/dz^2)^2]$. Note these are meaningless when either dU/dz or d^2U/dz^2 approaches zero. The notation is as follows: ϵ in ft^2/sec = eddy-diffusivity; τ in lb/ft^2 = unit-shear (constant with height only for logarithmic velocity-distribution); ρ in lb sec^2/ft^4 = mass-density; $\sqrt{\tau/\rho}$ in ft/sec = friction-velocity = $\ell\,(dU/dz) = \kappa\,[(dU/dz)^2/|d^2U/dz^2|]$; U in ft/sec = mean velocity parallel to ground at height z; and $|dU/dz|$ in sec^{-1} = velocity-gradient at height z (absolute value regardless of sign); (dU/dz) is usually positive because z is measured from the solid boundary-surface); z in ft = height above ground with subscript r = roughness-parameter for power-law, subscript ℓ = roughness-parameter for logarithmic law, and subscript o = dimensional factor for logarithmic law; ℓ in ft = mean mixing length (that is, double amplitude of eddy-waves); and κ = Von Kármán constant (= 0.40).

For the power-law distribution of velocity above a plane, which has been found most suitable for interpretation of observations made under stable conditions, more than one meter above a boundary-surface

$$U = U_1 [(z + z_r)/(z_1 + z_r)]^m$$

$$dU = [U_1/(z_1 + z_r)^m] \, d(z + z_r)^m$$

$$(dU/dz) = [mU_1/(z_1 + z_r)^m] \, (z + z_r)^{m-1}$$

$$(d^2U/dz^2) = \left\{[m(m - 1) \, U_1]/(z_1 + z_r)^m\right\}(z + z_r)^{m-2} \qquad \text{Negative for } m < 1$$

Hence the mixing-length expression for power-law interpretation is

$$\ell = \kappa \left| \frac{dU/dz}{d^2U/dz^2} \right| = \kappa \frac{(z + z_r)}{|m - 1|} = \kappa \frac{(z + z_r)}{1 - m}$$

Then the eddy-diffusivity is found directly from the observed power-law velocity-distribution

$$\epsilon = [\kappa^2 (z + z_r)^2 / (1 - m)^2] \, (dU/dz)$$

$$\epsilon = [\kappa^2 mU_1/(1 - m)^2][(z + z_r)^{m+1}/(z_1 + z_r)^m]$$

With power-law distribution, the friction-velocity, $\sqrt{\tau/\rho}$, is not constant with height, but can be evaluated at any level from the velocity at that level by using the second defining equation

$$\sqrt{\tau/\rho} = \ell \, (dU/dz) = \kappa \, [(z + z_r)/(1 - m)] \, (dU/dz) = [\kappa \, mU_1/(1 - m)] \, [(z + z_r)/(z_1 + z_r)]^m$$

Since $U = U_1 [(z + z_r)/(z_1 + z_r)]^m$, the friction-velocity with power-law distribution varies directly with velocity, namely $\sqrt{\tau/\rho} = \kappa \, mU/(1 - m)$.

If the conditions are such that interpretations should be made on the basis of logarithmic distribution of velocity above a surface, the evaluation of eddy-diffusivity and friction-velocity can be carried out as follows:

The logarithmic distribution of velocity above a plane is

$$U = (1/b) \, [\log_e (z + z_\ell + z_o) - \log_e z_o]$$

in which the roughness-parameter, z_1, is usually omitted (see Appendix I). Then

$$dU = (1/b)\left\{[d(z + z_\ell + z_o)/(z + z_\ell + z_o)] - 0\right\}$$

$$(dU/dz) = (1/b) \, (z + z_\ell + z_o)^{-1} = U_1 \, (z + z_\ell + z_o)^{-1}/\log_e [(z_1 + z_\ell + z_o)/z_o]$$

because

$$(1/b) = U_1/\log_e (z_1 + z_\ell + z_o/z_o)$$

and

$$(d^2U/dz^2) = - \, (1/b) \, (z + z_\ell + z_o)^{-2} = - \, U_1 \, (z + z_\ell + z_o)^{-2}/\log_e [(z_1 + z_\ell + z_o)/z_o]$$

$$= - \, [1/(z + z_\ell + z_r)] \, (dU/dz)$$

Hence the mixing-length expression for logarithmic distribution is $\ell = \kappa \, [(dU/dz)/|d^2U/dz^2|]$ $= + \, \kappa \, (z + z_\ell + z_o)$. Then $\epsilon = \kappa^2 \, (z + z_\ell + z_o)^2 \, (dU/dz) = (\kappa^2/b) \, (z + z_\ell + z_o)$ $= \kappa^2 \, U_1 \, (z + z_\ell + z_o)/\log_e [(z_1 + z_\ell + z_o)/z_o]$.

The constants z_ℓ and z_o can be determined as previously described--the value of z_o from the extrapolation to zero-velocity and the z_ℓ (if used) from the displacement of the height-scale needed to bring the velocity-observations to a straight line on semi-log plotting.

Since the logarithmic law gives the friction-velocity, $\sqrt{\tau_o/\rho}$, explicitly because it is considered constant with height, this characteristic can be evaluated as follows: From the square root of the second defining equation $\sqrt{\tau/\rho} = \ell\,(dU/dz) = +\kappa\,(z + z_\ell + z_o)\,(dU/dz) = +\,(\kappa/b) = +\,\kappa\,U_1/\log_e[(z_1 + z_\ell + z_o)/z_o]$, in which all of the constants are known as above.

The limitations of the foregoing expressions prevent the determination of values of eddy-diffusivity in density-currents within the foliage-layer of the orchard. However, values found above the tree-tops and also close to the bare ground are reported in Table 4, and if the over-tree values are plotted log-log, they would yield curves somewhat similar to those in Figure 1 because both velocity and eddy-diffusivity are power-functions of height. The indeterminateness of eddy-diffusivity within the tree-foliage zone seriously hampers studies of heat-transfer, but this very application constitutes a second approach, and it is hoped that further intensive study will reveal at least an approximate method for determining eddy-diffusivity in the foliage-layer by simultaneous interpolation of shear, mixing length, and rate of heat-transfer in some consistent manner.

Table 4--Eddy-diffusivity, feet^2/sec, from velocity-profiles of Figure 3 ignoring density-pressure gradient

Velocity-group	Heights above ground, z, feet										
	0	0.5	2	4-5	7-12	14	20	25	30	40	50
I	0.0036	0.021	0.012	0?	?	0.43	2.0	2.7	0	0	0
II	0.0056	0.034	0.055	0?	?	0.96	3.3	4.6	0	0	0
III	0.0062	0.037	0.087	0?	?	0.99	3.3	4.7	8.4	14.4	15.4
IV	0.0076	0.046	0.061	0?	?	1.61	5.7	10.0	14.8	25.8	38.6
V	0.0126	0.076	0.205	0?	?	3.28	12.1	20.8	28.1	58.1	87.7

Summary

Velocity-distribution--It was found that the velocity-data obtained at Riverside can be approximated by a power-function of the form $U = c(z - z'_r)^m$ where c and m are constant for any particular velocity-profile. When the velocity at 20-foot elevation is less than about three miles per hour, m has a value of approximately 1/3, which is the value deduced by SVERDRUP for the exponent, $(1 + n)/4n$, on the basis of similarity of velocity- and temperature-distributions. Theoretically, the exponent should decrease as the velocity at a given height increases. However, these data indicate that the exponent m may increase somewhat with increased velocity.

The data are too meager to indicate any definite relation between roughness-parameter z'_r and velocity or inversion. The average value of z'_r was found to be ten feet. If the tree-height is taken as 11 to 12 feet, the roughness-parameter with respect to the tree-tops (z_r) is one to two feet.

Eddy-stability--According to RICHARDSON'S criterion of atmospheric stability, the conditions prevailing during nights when orchard-heating studies were conducted at Riverside were generally those of great stability (Ri > 1) or nearly so. The least stability, according to this criterion, occurs just above the tree-tops. Although the gradient of temperature-inversion is greatest in this region, the wind-velocity gradient here is also at its maximum. The velocity-gradient enters the stability-criterion in the second power, while the temperature-gradient is in the first power, resulting in the minimum Ri just above the tree-tops. This seems unreasonable and indicates the stability-criterion is not directly applicable to density-currents. In the case of density-flow of cold air beneath stationary warm air, the velocity-gradient would go to zero at some height, resulting in eddy-decay. This condition favors the development of strong inversions. The stability-criterion is decreased when the wind-velocity increases or when the temperature-inversion decreases below about 10° temperature-difference between 5-foot and 60-foot elevations.

Eddy-diffisuvity--The values for eddy-diffusivity found from these data above the tree-tops give a log-log plot similar to Figure 1, because both velocity and eddy-diffusivity are power-law functions of height, except above the 25-foot level for the two lowest velocity-groups. The calculated values are much too great presumably due to the nature of density-flow of cold air down a slope under a relatively stationary warm air. Within the foliage-zone the formulas do not apply. For this region of tenuous restriction to flow there is no adequate analytical treatment. Possibly some rough idea of the magnitude of diffusivity can be obtained by interpolating the shear, the mixing length, and heat-transfer rate in some consistent manner. This question needs thorough and intensive discussion.

Appendix I--Roughness-parameter in logarithmic distribution of velocity

Investigations of fluid flow in pipes have shown that velocity-profiles can be well represented by a logarithmic expression. PRANDTL [8, equation (5)] gives this logarithmic law for flow over a horizontal surface as

$$U = (1/\kappa)\ (\sqrt{\tau_o/\rho})\ [\log_e\ (z/z_o)]$$

and he states [p. 190]: "z_o is a constant of integration," which he says may be related to surface-roughness, but that research on that question is not completed. PRANDTL also states that considering a surface of sand-particles, z_o might be taken as one-thirtieth of the diameter of the particles.

ROSSBY and MONTGOMERY [2, equation (1)] introduce a surface-depth constant, z_o, into the mixing-length expression

$$\ell = \kappa\ (z + z_o)$$

because ℓ has a finite value at the ground. In other words, the frictional stress (τ) must be finite at the surface where z is zero. ROSSBY and MONTGOMERY [2, equation (3)] express this in the equation

$$\tau = \rho\kappa^2\ (z + z_o)^2\ (dU/dz)^2$$

In the above, PRANDTL'S logarithmic expression [5] is the integration of the friction-equation [3] of ROSSBY and MONTGOMERY (PRANDTL'S $z = z_o$ at $U = 0$). And hence the z_o in both must be identical and is not an independent roughness-parameter. The logarithmic expression must be of the form $z = z_o\ e^{bU}$. Without z_o, the zero-value of height ($z = 0$) would be meaningless because mathematically it would be found where the velocity was negatively infinite. This z_o is evaluated as the constant of integration $= -\ [(1/\kappa)\ (\sqrt{\tau/\rho})\ \log_e\ z_o]$ by taking the stream-velocity, U, to be zero at $z = 0$. Graphically this is the intercept on the [log $(z + z_o)$]-scale at zero on the arithmetic velocity-scale.

It is to be noted that the rate of shear must be finite near any surface because of the laminar sub-layer and buffer layer [9]. This fact is in favor of the logarithmic interpretation of velocity-distribution as against the power-law interpretation because for the latter (dU/dz) goes to zero asymptotically as U approaches zero. The unique application of the logarithmic law for all cases near a surface is confirmed by the straight line obtainable by semi-log plotting of A. C. BEST'S wind-profile under comparatively stable conditions. For this case the power-law (log-log) would ordinarily be preferred, but seems to be unusable for observations close to a real surface.

If a logarithmic interpretation is to be made of a velocity-profile over tree-tops or brush, there must be some distance, z_ℓ, between a physical level and the zero-level as found by extrapolating the velocity-profile. Introducing such a distinct parameter, z_ℓ (separately from the dimensional factor z_o) the whole logarithmic expression becomes

$$z + z_\ell + z_o = z_o\ e^{bU}$$

In this case, a positive z_ℓ represents the thickness of an equivalent layer of air from the top of a rough surface down to an imaginary plane surface, which would yield the same drag as is produced by the actual rough surface. Hence the complete form of expression for logarithmic velocity-distribution above a surface is

$$U = (1/b)\ \log_e\ [(z + z_\ell + z_o)/z_o]$$

The constant $(1/b)$ can be evaluated from the slope of the line of observed velocity when plotted on semi-log scales or can be expressed in terms of observed velocity at a given level.

$$(1/b) = U_1/\log_e\ [(z_1 + z_\ell + z_o)/z_o]$$

Thus

$$U = U_1\ \log_e\ [(z + z_\ell + z_o)/z_o]/\log_e\ [(z_1 + z_\ell + z_o)/z_o]$$

In plotting observations of wind-velocity versus log of equivalent height (that is, semi-log graph), the sum of $z_o + z_\ell$ is found by trial (in the same manner as z_r for power-law representa-

tion) by shifting of the height-scale to obtain the best straight line. The intercept of this line on the height-ordinate at zero-velocity gives the dimensional factor z_o. Then the roughness-parameter z_ℓ is determined by subtraction.

Although observations at only three levels are inadequate to establish a reliable wind-profile, it may be of interest to note that a curve drawn through the points shown in Figure 2 of ROSSBY and MONTGOMERY [4] would show slight concavity upward. By reinterpreting these data (HELLMAN [10] for strong winds at Nauen between 9^h am and 3^h pm for the year) it is found that the velocity-observations at 2 m, 16 m, and 32 m will lie exactly on a straight line when plotted semi-log if in the height-expression $(z + z_\ell + z_o)$, $z_\ell + z_o$ is taken as -0.69 m. Then z_o given by ROSSBY and MONTGOMERY as 0.55 cm for $z_\ell = 0$, reduces to 0.14 m.

The negative roughness-parameter does not seem reasonable; hence the observational data seem inadequate for such exact analysis. However, the measurements by A. C. BEST shown by SVERDRUP in his Figure 1 would also fall more closely on a straight line if the observations were plotted at lower log values. This also indicates a negative z_ℓ where SVERDRUP assumes the low-level readings are inaccurate.

Although the power-law is considered most suitable for interpreting velocity-profiles during stable conditions it may be of interest to note that A. C. BEST'S data for nocturnal inversions close to the ground are best interpreted logarithmically and indicate $z_\ell = 0$, and $z_o = 0.22$ cm. For power-law interpretation, HELLMAN'S Nauen data with light winds between 3^h and 6^h am indicate $z_r = +95$ cm.

In comparing the power-law and the logarithmic law, SVERDRUP [3] states, "One might expect that the logarithmic law would have a wider application than the power-law, but this is true only in case of indifferent equilibrium (when the lapse-rate equals the adiabatic rate) since the velocity-distribution in the vicinity of a boundary-surface is modified by the stability."

Appendix II--Abstract of derivation of Richardson's [6] number

RICHARDSON finds a criterion for turbulence in the relation of rates of transformation in eddies of heat and gravitational energies versus REYNOLDS kinetic energy due to wind-shear. This is expressed in his equation No. 5.3 (with some change of symbols) as

$$\frac{\partial E'}{\partial t} - \frac{2\mu\pi^2}{\rho\ell^2}E' = \iint \mu_\epsilon \left[\left(\frac{\partial \bar{u}_x}{\partial z}\right)^2 + \left(\frac{\partial \bar{u}_y}{\partial z}\right)^2 - \frac{g}{\gamma p}\frac{\partial \sigma}{\partial z}\right] dz dA$$

where E' in erg = kinetic energy associated with the deviations of the velocities (from means) $+ (1/2)\rho(u_x'^2 + u_y'^2 + u_z'^2)$ zA, t in sec = time, μ in gram wt × sec/cm^2 = molecular viscosity (absolute), μ_ϵ in gram wt × sec/cm^2 = eddy-viscosity (absolute) = (1/g) × eddy-conductivity [11] = (1/g) × (100 grm sec^{-1} cm^{-1}) at one km [p. 363], ρ in (1/g) × gram wt/cc = mass-density, ℓ in cm = linear size of an eddy ($\ell^{-2} = n_x^{-2} + n_y^{-2} + n_z^{-2}$, where the size of the cell is $n_x \cdot n_z$ cm in plane of the motion, and n_y at right-angles to the motion), $\bar{u}$ in cm/sec = mean velocity, subscripts denote line of travel, g in cm/sec^2 = acceleration due to gravity, γp in ergs/°C per gram wt/g = thermal capacity per mass at constant pressure (in units of work; = 4.186 × 10^7 × thermal capacity of cal/°C per gram wt/g), σ in ergs/°C per gram wt/g = entropy per mass, $(\partial\sigma/\partial z)$ in ergs/°C per gram wt/g per cm = entropy-gradient upwards = $(1/\Theta)$ $[\gamma p(\partial\Theta/\partial z) + g]$, where Θ = absolute temperature °K [equation (4.16)], $(g/\gamma p)(\partial\sigma/\partial z)$ in sec^{-2} = buoyancy damping term--on clear days in troposphere is of the order of 10^{-4} sec^{-2} [p. 363], $\mu_\epsilon(g/\gamma p)(\partial\sigma/\partial z)$ in erg/sec cc = convective activity per volume lost by the eddies [p. 363], x, y, z in cm = coordinate distances with z vertical, and A in cm^2 = horizontal plane area = xy.

The first term on the left, $(\partial E'/\partial t)$, is the rate of production of kinetic energy in eddying due to wind-shear. The second term, $(2\mu\pi^2/\rho\ell^2)E'$, is the rate of dissipation of eddying kinetic energy by molecular viscosity (which produces heat). RICHARDSON'S criterion distinguishing between the persistence of eddies and the dying away of eddies is the equating of these two terms, which requires that the right-hand terms $(\partial u_x/\partial z)^2 + (\partial u_y/\partial z)^2 - (g/\gamma p)(\partial\sigma/\partial z)$ equal zero. "That is to say, the change of about one meter sec^{-1} in 100 meters of height would be the critical value (for turbulence) on an average clear day in the troposphere" [p. 364]. "Equation (5.3) also shows that, when the day wind is sufficiently strong $(\partial\bar{u}/\partial z)^2$ will overpower the term in $(\partial\sigma/\partial z)$, so that eddies will continue to exist and to supply momentum to the surface-air, even on a clear night." . . . . "At Benson, for example, where the anemometer-head is 26 meters above the plain,

the day wind usually dies away on a clear winter night if it is five meters/sec but not if it is 11 meters/sec. . ." In a later paper, RICHARDSON shows that this criterion can be written [12]

$$(\partial u_x/\partial z)^2 + (\partial u_y/\partial z)^2 = (g/T)\,[(\partial T/\partial z) - (\partial T_A/\partial z)]$$

where $(\partial T/\partial z)$ is the "up-gradient of temperature" (= negative lapse-rate) and $(\partial T_A/\partial z)$ is the adiabatic up-gradient of temperature (= -1°C/100 m when no condensation occurs).

It is to be noted that in this derivation RICHARDSON has not treated a non-uniform variation of shear-stress with height which occurs in density-currents due to irregular distribution vertically of the density-pressure gradients which produce nocturnal flow of cold air even on very slight slopes.

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NOTE ON THE VARIATION OF WIND WITH HEIGHT IN THE LAYER NEAR THE GROUND

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Of the various meteorological problems involving turbulent-mass interchange one of great concern to hydrology and agriculture is the transport of moisture between an evaporating surface and the atmosphere. For several years we have been working on this problem in the Soil Conservation Service, and from time to time various members of the staff have reported on the progress of our work [see 3, 7, 8, 9, 10, 11, 12, 13, 14 of "References" at end of paper]. During the last year we have concentrated on the problem of measuring wind-velocity.

Considering the importance of the wind-structure in the determination of the characteristics and magnitude of the coefficient of eddy-conductivity it is surprising that there are in existence so few good observations of wind-velocity at various levels in the lowest ten meters of the atmosphere.

There are serious instrumental difficulties in making accurate measurements of wind-velocity. The frictional resistance and inertia of the familiar whirling cup-type anemometer are such that correction-factors obtained in a wind-tunnel for steady flow do not yield true mean values for the varying velocities encountered in the free atmosphere. Not much attention has been given

by meteorologists to the measurement of low velocities; consequently the instruments are designed to withstand high velocities that few of them ever encounter but they stop altogether at low wind-speeds that occur almost daily. It is not easy to find a number of anemometers whose starting speeds, stopping speeds, and running speeds are identical. Thus when simultaneous measurements are made with a number of anemometers at different levels the difficulties are multiplied and there may be considerable error in measurement, particularly in the low-velocity range near the ground. Going downward in the wind-profile, velocities below the running speeds of the anemometers occur during an increasing fraction of the time; thus it is necessary as a first step to have carefully matched instruments for comparing velocities at different levels.

Recent studies on the structure of the wind near the ground have all utilized the same observations: Those published by HELLMANN [2], SHAW [5], WÜST [15], BEST [1], and SVERDRUP [6]. These data are neither very numerous nor free from instrumental error. For example, the stopping speeds of the three anemometers used by SVERDRUP were 1.2, 0.6, and 0.5 meters per second; thus the measurements at the three levels are not strictly comparable. BEST used three different types of anemometers. His data are averages of a number of three-minute experiments in which all velocities under 1.5 m/sec (3.36 mi/hr) were discarded. They are not tabulated by time of day or season of the year. Many of these published data have been treated statistically in such a manner that they are no longer capable of answering certain important questions. For example, the velocities at various levels may be reduced to ratios of the velocity at a standard level. Sir NAPIER SHAW published some data reduced in this way and then stated that "the ratio of decrease appears to be independent of the magnitude of the velocity but dependent upon the nature of the surface" [5, p. 123]. In the form in which SHAW'S data are published, they cannot possibly demonstrate that the wind-profile is independent of velocity.

Only a decade ago SHAW [5, pp. 125-126] wrote, regarding the law of wind-structure in the layer near the ground: "The precise formula to be adopted is however not a matter of great practical importance." The realization that a precise law of wind-structure is required for the solution of numerous problems involving transfer has come mainly within the last ten years. To obtain such a law, observations taken throughout the day and at various seasons of the year, providing accurate measurements at various velocities, during different conditions of atmospheric stability and over different kinds of surfaces, are indispensable.

Most workers have used either a power law or a logarithmic law in attempting to express the relationship between wind-velocity and height. The power law has usually taken the form

$$u = u_1 z^a \tag{1}$$

where u is wind-velocity at height z and u_1 is wind-velocity at unit-height. The logarithmic law is of the type

$$z = z_0 a^u \tag{2}$$

or

$$u = (\log z - \log z_0)/\log a \tag{3}$$

where $\log z_0$ is the y-intercept and log a the slope of the straight line obtained by plotting log z as ordinate and u as abscissa. The weight of observational evidence has led to a preference for the logarithmic law. Furthermore, the theoretical formulation developed by the PRANDTL school requires that the vertical distribution of wind-velocity follow a logarithmic law in the part of the turbulent layer where shearing stress, τ, and density, ρ, may be assumed constant [4, p. 6].

The purpose of this note is to present samples of observations made by the Soil Conservation Service in various localities during recent months and to outline some of the problems that they raise. Throughout the calendar year of 1939 continuous records were made of wind-speed at four levels in a meadow at Arlington, Virginia. Hourly values for the entire year are being published [13]. In 1940 observations of wind-speed at two or more levels were obtained for various periods of time from a station in California, five stations at the National Agricultural Research Center in Beltsville, Maryland, and 12 in Ohio. These observations are not good; the anemometers were not carefully matched and the recorders operated very unsatisfactorily. In 1941 we gave more attention to the problem of securing good wind-observations. From the 600 anemometers available we attempted to select those that operate similarly at low wind-speed. Continuous records of wind-speed at seven levels were made over a field of growing corn at the National Agricultural Research Center from July 1 to December 11. Early this year we began getting observations at six levels over a large reservoir in southern Texas and at 14 levels over an open field in Ohio. These observations are better than any we have had in the past and have led us to suspect the validity of the familiar logarithmic law.

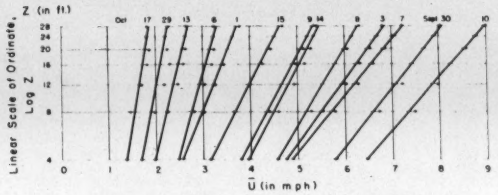

Fig. 1--Wind-velocity over corn-stubble field, Beltsville, Maryland, plotted against logarithm of height (Z)

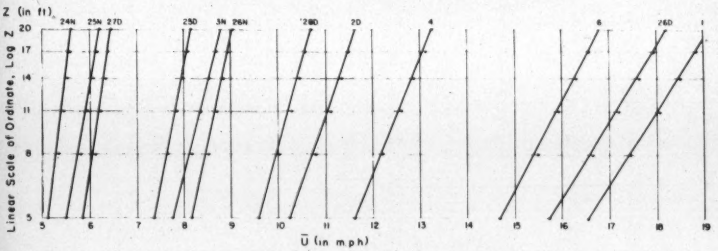

Fig. 2--Wind-velocity over Lake Corpus Christi, Texas, February 24-March 6, 1942, plotted against logarithm of height

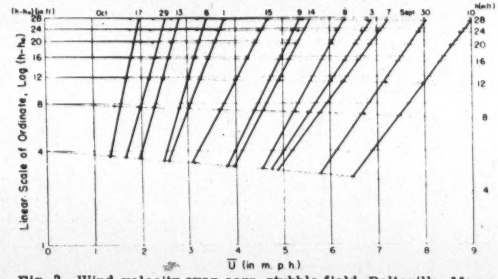

Fig. 3--Wind-velocity over corn-stubble field, Beltsville, Maryland, plotted against logarithm of effective height (h - h_o)

In Figures 1 and 2 average wind-velocities at various levels are plotted against the logarithm of height for representative periods at two localities. Records of individual days in October 1941 at the station over corn stubble are given in Figure 1. The daily record for February 24 to March 6, 1942, over the reservoir in Texas is represented in Figure 2. The actual observations are given in Tables 1 and 2.

It can be seen in these charts that there is a systematic departure from the logarithmic law. A line fitting the points is not a straight line but one with slight concave curvature. The three series of observations published by BEST [1, p. 37] also show the same deviation from a straight line when velocity is plotted against the logarithm of height. The failure of these observations to fall on a straight line suggested that the effective height of the anemometers is different from the measured height, and that an effective surface for turbulent transfer exists at a height h_o above

Table 1--Wind-velocity profiles over a corn-stubble field, Beltsville, Maryland, October 1941

Begin		End		Mean velocity at height of						
Date	Time	Date	Time	28 feet	24 feet	20 feet	16 feet	12 feet	8 feet	4 feet
	h m		h m	mph	mph	mph	mph	mph	mph	mph
Sep. 30	10 30A	Oct. 1	12 00N	8.04	7.91	.....	.....	7.11	6.73	5.79
Oct. 1	12 30P	2	12 42A	3.78	3.63	.....	3.44	3.27	3.03	2.59
2	12 00N	3	9 45A	3.44	3.27	3.23	3.12	2.90	2.62	2.39
3	10 00A	4	10 45A	6.81	6.68	6.54	6.33	6.02	5.54	4.75
4	11 00A	6	9 45A	3.90	3.86	3.81	3.75	3.59	3.30	2.93
6	10 00A	7	10 24A	3.23	3.22	3.25	3.18	3.04	2.83	2.49
7	10 36A	8	10 00A	7.22	7.03	6.86	6.60	6.28	5.80	4.88
8	10 12A	9	10 00A	6.32	6.14	6.06	.....	.....	5.28	4.56
9	10 24A	10	1 00P	5.36	5.21	5.13	4.97	.....	4.40	3.80
10	1 24P	11	9 30A	8.99	8.77	8.57	.....	7.97	7.48	6.45
11	10 00A	13	9 30A	4.24	4.19	4.18	.....	3.91	3.63	3.09
13	10 00A	14	9 30A	2.67	2.65	2.66	2.61	2.49	2.27	1.97
14	9 42A	15	3 00P	5.41	5.34	5.28	5.15	4.93	4.60	3.95
15	3 12P	16	9 42A	4.69	4.50	4.43	4.26	4.00	3.66	3.15
16	9 54A	17	10 36A	4.01	3.91	3.94	3.84	3.69	3.42	3.01
17	10 48A	18	9 06A	1.82	1.80	1.87	1.82	1.70	1.45	1.37
18	9 54A	20	12 00N	3.78	3.67	3.61	3.49	3.27	2.94	2.59
20	12 42P	21	8 12A	0.88*	0.87*	0.94*	0.88*	0.78*	0.67*	0.57*
21	8 30A	22	9 12A	5.31	5.14	5.07	4.89	4.64	4.30	3.69
22	9 30A	23	9 06A	2.63	2.60	2.66	2.62	2.47	2.27	2.02
23	10 00A	24	8 42A	8.37	8.19	8.02	7.83	7.48	7.27	6.07
24	9 12A	25	10 42A	5.32	5.11	4.99	4.82	4.52	4.21	3.47
25	11 06A	27	9 06A	4.48	4.35	4.33	4.26	4.07	3.28	3.16
27	9 56A	28	10 30A	3.83	3.68	3.62	3.50	3.29	3.03	2.61
28	11 00A	29	2 00P	6.68	6.40	6.27	6.20	5.90	5.56	4.83
29	2 30P	30	12 00N	2.28	2.21	2.26	2.31	2.18	1.95	1.68
30	12 24P	31	10 00A	1.96	1.99	2.03	1.99	1.84	1.51	1.38
31	10 42A	Nov. 1	12 05P	3.34	3.24	3.24	3.13	2.93	2.57	2.33

*Uncorrected.

Table 2--Wind-velocity profiles over Lake Corpus Christi, Texas, 1942

Begin		End		Velocity at height of					
Date	Time	Date	Time	20 feet	17 feet	14 feet	11 feet	8 feet	5 feet
	h m		h m	mph	mph	mph	mph	mph	mph
Feb. 24	5 37P	25	9 26A	5.627	5.599	5.538	5.460	5.348	5.133
25	9 33A	25	6 06P	8.169	8.094	7.992	7.851	7.660	7.345
25	6 16P	26	9 42A	6.219	6.163	6.069	5.961	5.819	5.499
26	9 53A	26	6 28P	18.222	17.938	17.632	17.214	16.659	15.751
26	6 30P	27	9 37A	9.046	8.944	8.855	8.717	8.518	8.166
27	9 44A	27	6 18P	6.451	6.388	6.336	6.240	6.116	5.829
27	6 26P	28	9 26A	5.530	5.492	5.468	5.410	5.314	5.041
28	9 38A	28	6 34P	10.725	10.602	10.487	10.291	10.034	9.566
28	6 42P	1	10 43A	9.285	9.277	9.136	8.899	8.663	8.436
Mar. 1	10 50A	2	9 08A	.....	18.852	18.501	18.079	17.469	16.543
2	9 16A	2	6 15P	.....	11.522	11.337	11.114	10.791	10.262
2	6 38P	3	9 54A	.....	1.989	1.908	1.815	1.925	1.691
3	9 59A	3	7 10P	.....	10.789	10.609	10.405	10.139	9.635
3	7 17P	4	10 20A	.....	8.691	8.538	8.358	8.171	7.769
4	10 30A	4	4 33P	.....	9.096	8.912	8.690	8.398	7.899
4	5 25P	5	6 30P	13.266	13.133	12.893	12.621	12.221	11.622
5	6 51P	6	10 45A	.....	4.549	4.445	4.383	4.252	4.037
6	11 00A	7	1 07P	.....	16.577	16.300	15.937	15.491	14.679

the actual physical ground- or water-surface, which is the origin of the coordinate system. If a source-surface actually exists at height h_o the wind-profile will have a curvature similar to that possessed by the observations, but could be brought to a straight line if plotted at the appropriate heights above the effective source-surface. In other words $z = (h - h_o)$, in which h rather than z represents the measured heights of the observations. The logarithmic law then becomes

$$h - h_o = z_o a^u \qquad (4)$$

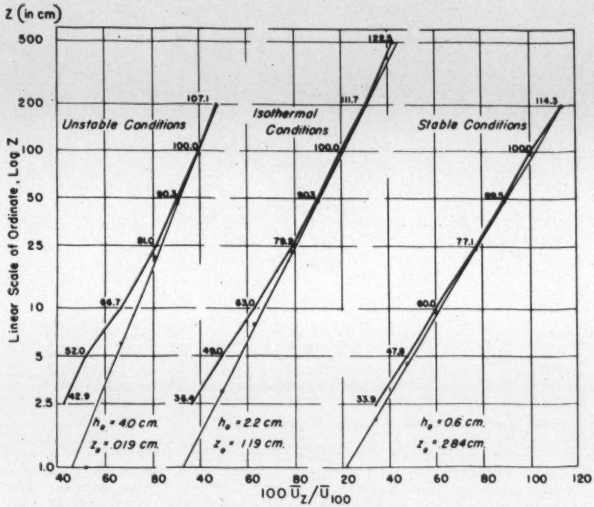

Fig. 4--Relative wind-velocity according to Best plotted against logarithm of height and of effective height ($h - h_o$) to show effect of stability on h_o and Z_o

or

$$u = [\log (h - h_o) - \log z_o]/\log a \qquad (5)$$

The observations of Figure 1 are replotted in Figure 3. Here an h_o is determined graphically for the observations of each day. It is seen that h_o varies directly with wind-velocity.

In fitting his data to a straight line, BEST [1, p. 37] plotted velocity against log (z - 1) and thus used an h_o of one cm, although apparently he did not realize that he was doing so. In Figure 4 BEST'S wind-velocity data for unstable, isothermal, and stable lapse-rates are plotted against log ($h - h_o$). The height h_o becomes less with increasing stability, being 4 cm, 2.2 cm, and 0.6 cm,

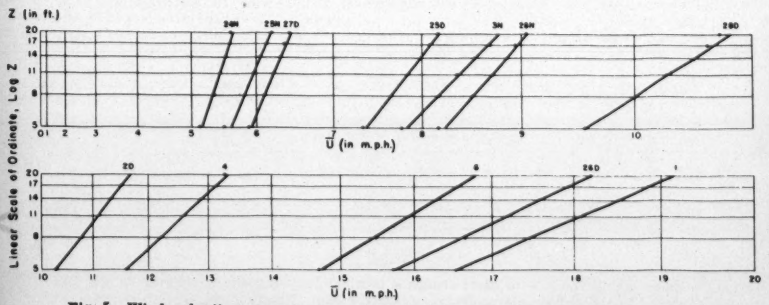

Fig. 5--Wind-velocity over Lake Corpus Christi, Texas, February 24-March 6, 1942 (Square of velocity plotted against logarithm of height)

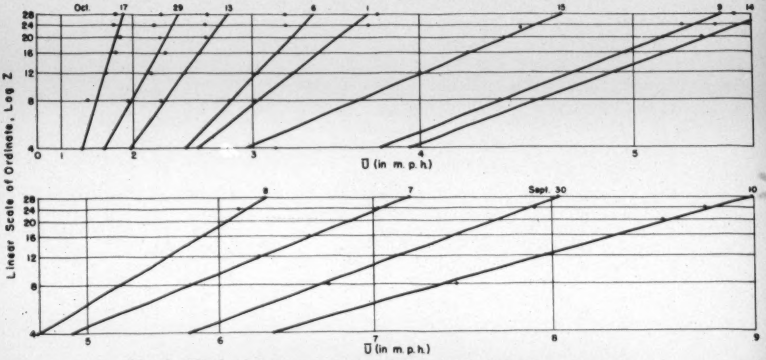

Fig. 6--Wind-velocity over corn-stubble field, Beltsville, Maryland
(Square of velocity plotted against logarithm of height)

respectively, in the unstable, isothermal, and stable cases.

The profiles of the wind over the lake surface exhibit the characteristic curvature when plotted on a semilogarithmic scale. This curvature is largely removed by reducing the effective height of the observations through the use of an h_o of 1.6 feet. Here the anemometers were 5 to 20 feet above the surface, whereas BEST'S instruments ranged between 2.5 and 200 cm.

The fact that the magnitude of the quantity h_o depends on the scale of height of the original observations indicates that "an effective source-surface for active turbulence" probably has no physical reality and suggests that the logarithmic law is of restricted validity.

If the square rather than the first power of the velocity is plotted against the logarithm of height practically no curvature remains in the profiles of the higher wind-velocities. In Figure 5 the observations from the Texas reservoir are replotted with u^2 against log z. It can be seen that the profiles for the periods when average velocity at the five-foot level is six miles an hour or more are closely fitted by straight lines. In Figure 6 the observations for October 1941 at the National Agricultural Research Center are plotted in the same manner and again the profiles for the days with higher velocities are closely fitted by straight lines. These observations were reworked to bring out the distinction between the daytime and nighttime hours and it was found that for the daytime observations the square of the velocity gives a good fit whereas the first power of velocity is adequate for the nighttime observations. Returning to BEST'S observations it is found that for the unstable case u^2 plotted against log z gives a very close approach to a straight line, whereas for the stable case a straight line is approached when $u^{1.1}$ is plotted against log z.

It appears, therefore, that a law which describes the change of wind-velocity with height more closely than any that has hitherto been formulated is a combination of logarithmic and power-laws.

$$u^p = (\log z - \log z_o)/\log a \qquad (6)$$

or

$$u = [(\log z - \log z_o)/\log a]^{1/p} \qquad (7)$$

When p is 0.1, equation (6) is approximately the equivalent of one expressing a linear relation between velocity and height

$$u = az + b \qquad (8)$$

which presumably represents the ideal condition in which turbulence is completely absent and momentum is transferred by intermolecular friction alone. Thus p is believed to vary between 2.0 with fully developed turbulence and some value less than 1.0 when turbulence reaches its smallest actual value.

The suggestion that in fully developed turbulence the square rather than the first power of the velocity varies with the logarithm of height comes from BEST'S observations as well as from our own. However, we need many more reliable observations. Should this new law of wind-structure be confirmed by other observations it will be necessary to reexamine the theory of fluid turbulence as developed by the PRANDTL school, and the accomplishment of our objective, the determination of evaporation from land- and water-surfaces, may consequently be delayed.

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THE MEASUREMENT OF WIND- AND MOISTURE-GRADIENTS OVER A RESERVOIR

J. C. Owen and M. H. Halstead

For several years the Soil Conservation Service has been working toward the development of a method for determining the evaporation from land- or water-surfaces. The method employs wind- and moisture-gradients in measuring the water-vapor transport from the surface to the atmosphere.

A year's record of evaporation from a land-surface was obtained by this method and published in the Transactions of the American Geophysical Union of 1940 [see 1 of "References" at end of paper]. Difficulties encountered with the hair hygrometer used during the time the first station was operated led to the development of the chemical absorption-hygrometer described in the Transactions of the Union of 1941 [2]. In June 1941 an evaporation-station was installed in a cornfield at the National Research Center at Beltsville, Maryland. There the absorption-hygrometer was operated in the field for six months and proved satisfactory.

In connection with a survey of Lake Corpus Christi (a large reservoir 30 miles from the mouth of the Nueces River in South Texas), currently being made by the Soil Conservation Service, data on evaporation were desired. This provided an opportunity for adapting the installation,

Fig. 1

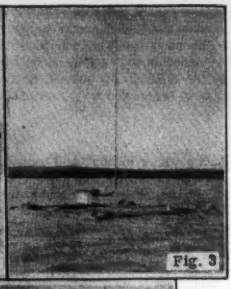

Fig. 3

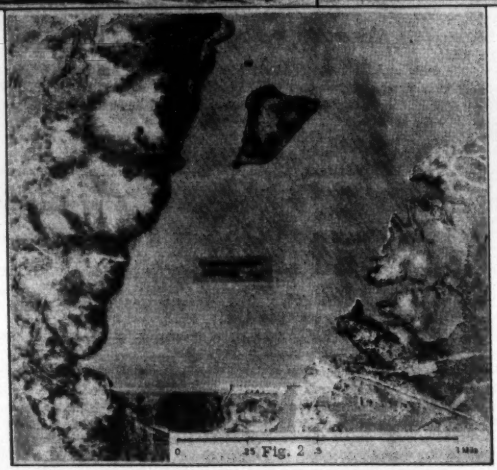

Fig. 2

previously used over land, to the measurement of water-vapor losses from a free water-surface.

In order to obtain representative values of the wind- and moisture-gradients it was necessary to mount the instruments on a float that could be anchored near the center of the lake. It was also necessary that the float offer the least possible resistance to air-flow and yet be large enough to minimize rocking with the waves and strong enough to withstand the high winds and rough water frequently encountered on the lake.

To satisfy these requirements a skeleton structure of two-inch by four-inch pine timber 18 feet square and four feet deep was built and substantially cross-braced to support the weight of a 20-foot instrument-mast in the center. All important joints were bolted. A 50-gallon oil-drum was bolted into each of the four upper corners to add buoyancy (Fig. 1). By partly flooding these drums the level of the float can be adjusted so that all but two inches of the framework and six inches of the drums are below the surface. As the dry lumber absorbs water, corresponding amounts of water can be pumped from the drums to hold the water-line constant.

The 20-foot mast of one-inch pipe supports anemometers and air-intake tubes at heights of 5, 8, 11, 14, 17, and 20 feet above the water-surface. While it would be advantageous to obtain records nearer the water, the frequent occurrence of high choppy waves on the lake make it unsafe to install instruments at a lower level.

The completed float was towed to the position shown on the map in Figure 2 and anchored. A single anchor-chain, attached by a bridle to the two corners farthest from the instrument-shelter, was used. Since the raft maintains a position down-wind from the anchor, this minimizes the influence of the instrument-box on the air-flow (Fig. 3). The anemometers were mounted on the anchor-side of the mast and, therefore, are always to windward.

The instruments are serviced daily and 24-hour mean values of wind- and moisture-gradients are obtained. On days when the lake is too rough for the operator to venture out in a power-boat the records are combined with those of the following day.

Over a smooth water-surface the wind-gradient was expected to be less than over land and consequently its determination required anemometers more accurately calibrated than those previously used. In order to obtain the required accuracy, 100 standard Soil Conservation Service type three-cup anemometers were tested against one of the same type that had been calibrated in the wind-tunnel of the National Bureau of Standards. The tests were made on an eight-arm variable-speed whirler by means of which starting speeds and running speeds could be compared accurately with the calibrated instrument. The six that agreed most closely were selected for use. They should not be in error by as much as 0.05 mi/hr in ten mi/hr. These anemometers operate electrical counters that are housed in the water-tight instrument-box on the edge of the float.

Two chemical absorption-hygrometers, also housed in the instrument-box, are used for measuring absolute humidity. Each hygrometer contains a continuously-operating electrically-driven pump of known volume that uses a medical syringe as cylinder and piston. On alternate strokes the pump draws air from intake-tubes at one of two levels. The air-samples pass through U-tubes containing a chemical desiccating agent, which retains the water-vapor, allowing it to be weighed.

In order to check one hygrometer against the other, each has an air intake at the eight-foot level. One instrument also draws air from the 20-foot level, and the other from the five-foot level. By means of air-intake tubes already installed, the hygrometers can be connected to any four of the six levels at which wind-measurements are made.

While the station has been in operation only a short time, the available data, presented elsewhere by THORNTHWAITE [3], strongly suggest that in the lower levels the square of the air-speed, rather than the speed itself, increases as the logarithm of height.

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METEOROLOGICAL PROBLEMS OF THE AMERICAS

R. H. Weightman

With the apparently slight connection that exists between weather-conditions in the Northern and Southern Hemispheres, it was natural for many years that only a mild academic interest existed on the part of North American meteorologists regarding weather-conditions and problems of South America. The same was largely true on the part of South American meteorologists with regard to weather-conditions and problems of North America. In recent years, however, with the advent of rapid and dependable radio communications and speedier transportation-facilities due to the development of commercial air-routes, daily exchanges of weather-observations not only between countries but between continents became necessary.

In North America with its great extremes of climate and its cold waves, storms, and hurricanes, there have been incentive and opportunity to develop a service for the benefit of agriculture, commerce, and navigation. This development required an increasing number of synoptic reports

from a network of stations extending from the tropics northward to the arctic and from the Pacific eastward to the Atlantic. As a consequence of these requirements, a very close collaboration developed between the United States, Canada, and Mexico in exchange of daily observations. This collaboration has involved codes, hours of observation, frequency of observations, units employed, circuits, etc. In all cases we have met with unfailing cooperation of our two neighbors.

In South America collaboration of this kind was confined largely to countries of temperate latitudes until the more recent developments of commercial air-lines. It seems fair to say that the growing demands of aviation lead to a series of conferences held in South America which has done more for promoting the broad relations in meteorology on that Continent than anything that has ever taken place. The first of these was held at Rio de Janeiro, Brazil, September 26 to October 5, 1935, the second at Lima, Peru, September 16 to 23, 1937, and the third at Montevideo, Uruguay, February, 1939. At the Rio Conference was laid the foundation for the more complete articulation of meteorological relations between the countries of South America through the organization of Regional Commission III of the International Meteorological Organization. The latter is composed of representatives of practically all the meteorological services of the world and is divided geographically into broad Regional Commissions which hold meetings and discuss regional problems, making report and recommendations to the I.M.O. The second Conference was that of Regional Commission III, comprising the countries of South America, held at Lima where further progress in coordinating plans and procedures was made. The third Conference was another meeting of Regional Commission III held at Montevideo. All three of these Conferences had important and far-reaching results. Probably the most important of them was the inauguration of the twice-daily continental broadcast (Amer.-Sud) of weather-observations from Rio. Thus were made available for the first time synoptic reports twice daily from all the countries of South America, including pilot-balloon observations and ship observations. Another result of this Conference was the institution of the weather-broadcasts made four times daily from the Naval Station at Balboa in the Canal Zone. Such broadcasts cover the northern part of South America, Central America, and the West Indies and the southern part of North America. With the continental broadcasts from Arlington and San Francisco, the two continents are now thoroughly covered.

Reference has already been made to the Regional Commissions of the International Meteorological Organization. In the last few years Regional Commission IV, comprising the countries of North and Central America was organized. At the Montevideo meeting Resolution XXVII was adopted, in which it was proposed to hold a joint meeting of Regional Commissions III and IV (in North America) either at Toronto or Washington in 1941. Due, however, to the War and other considerations, it was necessary to postpone the joint meeting, which is now set for October 1-10, 1942, at Washington, D. C. At the same time there will be a meeting of the directors of all the meteorological services of the Americas. Already the Secretary of State has addressed special invitations to Ing. Alfredo G. Galmarini, President of Regional Commission III, and to Commander F. W. Reichelderfer, President of Regional Commission IV; also general invitations are going forward to the countries of the Americas included in the two Regional groups.

At a time when it is impossible to convene the International Meteorological Organization, such a conference should have an important bearing on the trends and development of meteorology.

Many vital questions will require consideration, as, for example, weather codes, units, broadcasts, instrumental procurement and usage, radio channels, meteorological instruction, whether by correspondence course, conferences or in universities, installation and distribution of different types of stations, including pilot-balloon, radiosonde and robot, techniques of forecasting for different interests, exchange of visits, etc. While it is not likely that it will be possible to obtain definite solutions of all these problems, undoubtedly a great deal of progress can be made in arriving at a better understanding of the implications of these questions and a fuller appreciation of the resultant changes or modifications in present arrangements that will be required due to the War. The opportunity of meeting together and indulging in a free exchange of ideas on common problems should have not only immediately beneficial results but should lay a groundwork for the future development of meteorology in this Hemisphere.

U. S. Weather Bureau,
Washington, D. C.

COMPUTATION OF MAXIMUM POSSIBLE PRECIPITATION

A. K. Showalter and S. B. Solot

The Hydrometeorological Section of the United States Weather Bureau was organized late in 1937 and invested with the responsibility of applying the latest methods of air-mass analysis to the problem of determining limiting rates of precipitation. The guiding principle adopted at that time was to improve and refine accepted techniques of the hydrologic engineers rather than attempt radically new developments.

Various statistical studies of rainfall intensity-frequency-duration relationships had been made by the hydrologists but since these studies were concerned primarily with station-rainfall they had been proven inadequate for estimating the distribution of rainfall over a design river-basin.

The method of storm-transposition developed by BERNARD, HATHAWAY, and others was adopted by the Hydrometeorological Section as a fundamental technique. Briefly, the method of storm-transposition assumes that the ultimate flood in any basin cannot be determined solely from the rainfall-experiences on that basin, but must be based upon all outstanding floods in neighboring basins. In refining the method of storm transposition the obvious steps were:

(1) A thorough synoptic analysis of surface and upper-air conditions during the major storms
(2) Consideration of the location of the storms' occurrences with respect to geographical and topographic features as well as their position within the general circulation-pattern of the atmosphere
(3) The magnitude and persistence of the important causative phenomena producing heavy rainfall
(4) Determination of the physical upper limits of each of the causative phenomena
(5) Extrapolation of storm-rainfall in proportion to the possible increase in each of the controlling factors
(6) Transposition of the extrapolated storm with adjustments for its new location

Rigid application of the above methods to all of the major storms led to the conclusion that all intense rainfall was caused by one of the following synoptic patterns occurring singly or in combination:

(1) Quasi-stationary front with active minor waves
(2) Rapidly developing waves along a major front
(3) Major occluded cyclonic systems
(4) Decadent tropical cyclones
(5) Local or frontal thunder-storms
(6) Orographic rain

The common features of all these types are:

(1) Potential instability in the warm moist air
(2) Above-normal moisture charge below three km in the warm air
(3) Pronounced convergent flow in the lower levels

Since the moisture-charge in the lower levels appeared so important, the first refinement applied to the storm-transposition was an adjustment for greater possible depths of precipitable water in the warm sector. The original adjustment-chart was adapted from a survey of the mean moisture-charge in tropical maritime air.

The causative factor next in importance is the rate of flow of warm moist air into the zone of precipitation. Analysis of major storms over large areas revealed the consistent appearance of an intense cold cyclonic circulation aloft to the west of the principal rain-area. The steepness of this pressure-gradient aloft is largely controlled by the temperature-contrast between the warm and cold air-masses. However, since the warm-air characteristics are more conservative, the temperature and pressure in the cold air-mass become the governing factors.

Further studies established an approximately linear relationship between pressure and temperature at the five-km level (Fig. 1). DINES [Met. Office Geophys. Mem. No. 13] had previously shown a good correlation between pressure at the nine-km level and the mean temperature of the column below, but it was necessary to use the five-km level because that was the maximum height of most of the available soundings. The conclusion drawn from these pressure-temperature surveys was that minimum values of pressure at the five-km level can be predicted from the minimum values of temperature at that level. A complete survey of the extreme minimum temperatures at five km was made and is being kept up-to-date. The minimum temperatures reported at five km in the rear of major storms were in each case compared with the extreme temperature of record at that height for the locality and season. In a remarkably high percentage of cases the major storms equaled, approached, or produced the extreme minimum temperatures at five km for the locality and season. In most of the outstanding major storms it was therefore assumed that more rapid rates of inflow of moist air could not occur.

The next important development was the use of dew-points in the warm sector as a measure of the precipitable water in the moist air. When intense convergence occurs in the warm sector, moist air in the surface-layers is carried upward and cooled at the pseudo-adiabatic rate. In the center of an intense convective column, then, the total water-vapor is equivalent to that in a saturated column of air with pseudo-adiabatic lapse-rate and a surface dew-point equal to the observed dew-point. Since surface-pressure in the warm sector of the major storms generally approaches 1,000 millibars, a chart was devised expressing precipitable water in a saturated column of air, above that level and with pseudo-adiabatic lapse-rate, as a function of surface dew-point (Fig. 2). Moisture-charge computed from this chart on the basis of observed dew-points was compared with the amounts of precipitable water computed from upper-air soundings. The agreement was always especially good when the soundings were obtained well within a convergent warm sector.

The establishment of the reliability of the dew-point technique paved the way for two additional fields of investigation: (1) The extension of knowledge of the moisture-charge in the warm sector to all major storms of record; dew-points have been observed for 100 years but upper-air soundings, from which precipitable water can be computed directly, have been made over limited areas for approximately only 15 years; (2) the use of the sea-surface temperatures in the source-region of moist air as a measure of the limit of moisture-charge. This is based on the rather elementary assumption that the surface vapor-pressure in the air cannot be higher than the saturated vapor-pressure corresponding to the sea-surface temperature. If it were, condensation would occur on the oceanic surface. Generally the temperature of the air is one or two degrees above the sea-surface temperature and the dew-point therefore is two to four degrees below the sea-surface temperature. Ocean-surface temperatures rarely go above 82°F and observed dew-points above 80°F are exceedingly rare. A moisture-charge equivalent to that in a saturated column of air with

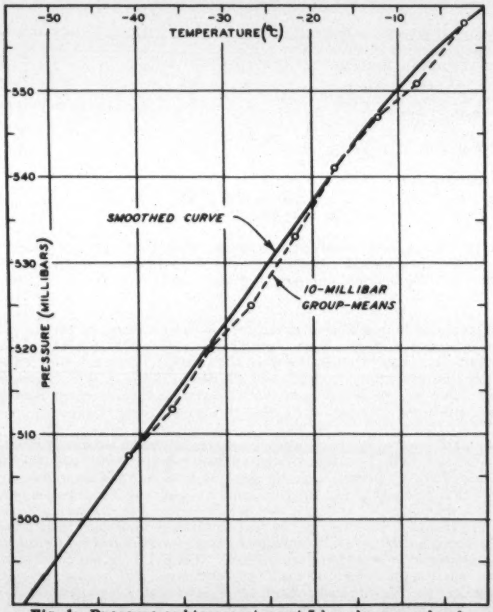

Fig. 1--Pressure and temperature at 5 km above sea-level, January 1938, grouped means (United States Weather Bureau airplane observations form 1109-AER)

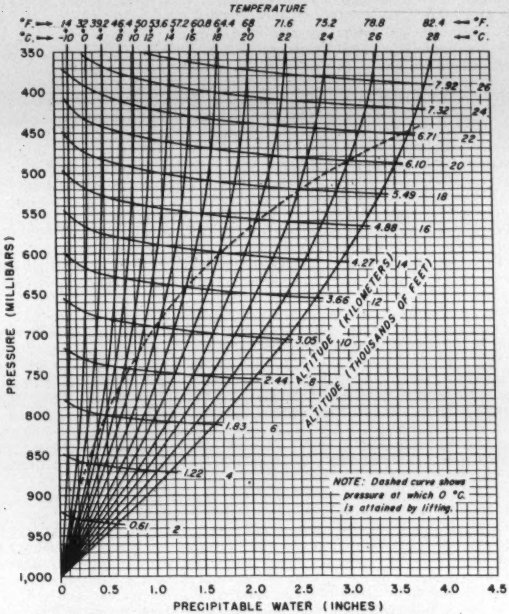

Fig. 2--Depths of precipitable water in a column of air of given weight above 1000 millibars assuming saturation with a pseudo-adiabatic lapse-rate for the indicated surface-temperatures

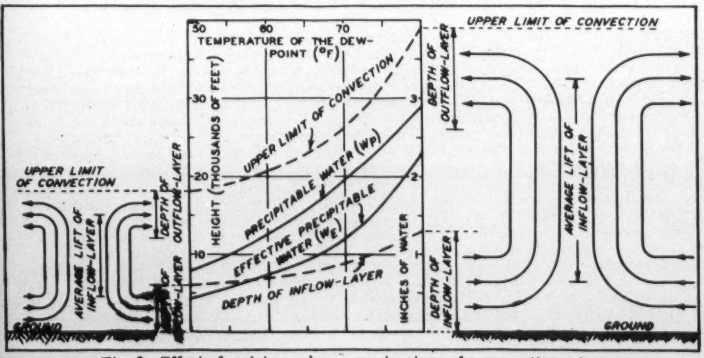

Fig. 3--Effect of moisture-charge on structure of a convective cell

pseudo-adiabatic lapse-rate and surface dew-point of 80°F is therefore considered a maximum upper limit for any place in continental United States. Also, it can safely be stated that no major storm will occur in the continental United States with dew-points in the warm sector lower than 50°F. However, any reasonable engineering technique must make adjustment of the upper limit for season, latitude, and elevation.

Knowing that precipitation bears a direct relationship to the moisture-charge and the rates of inflow of the warm air, it seems logical to postulate a simplified flow-model in order to calculate intensities of precipitation over drainage-basins of selected shapes and sizes. From simple geometrical and arithmetical assumptions one can easily calculate rates of inflow of moist air. Consider, for example, a rectangular area with moist air flowing in across the end of the rectangle. The net volume of inflow in unit-time is the product of the depth of the column, the inflow-width of the rectangle, and the velocity of the air. Since the quantity of air is not important, the depth of available precipitable water within the air must be used for the vertical dimension and the volumetric inflow of water in the form of water-vapor therefore calculated directly. Assuming all incoming water to be precipitated, then dividing by the area of the rectangle, the result is the average depth of precipitation over the rectangle in unit-time. For small areas a similar computation can be made by assuming radial inflow across the basin-boundary.

The obvious defect in the above approach is the implication that all moist air that passes over the basin must be completely dessicated before leaving it. It would be more reasonable to determine the percentage of available precipitable water which can be precipitated by natural processes.

The most efficient precipitating mechanism is a convergent convective cell. In such a cell deep layers of moist air flowing radially inward are lifted to great heights and then undergo radial outflow. The amount of moisture which can be precipitated depends on the depth of the inflow-column, the height to which this column is lifted, and the difference in moisture-charge between the inflowing column and the outflowing column. Previous developments had already suggested the means of determining the moisture-charge in such columns if their depths and altitudes are known.

A determination of the amount of moisture which can be precipitated is therefore limited by the knowledge of the vertical extent of the cell. One fairly obvious factor is the upper limit to which convection can penetrate. It is well known that convection attains much greater heights in tropical regions than it does in the temperate and polar regions and therefore appears to bear some direct relationship to moisture-charge. The heights attained by cumulonimbus tops at various latitudes were compared with the heights of the tropopause for those latitudes and found to be in good agreement. The mean cloud-heights, maximum cloud-heights, and mean tropopause-heights for various latitudes were considered in relation to the mean oceanic temperatures for those latitudes, and a profile of the upper limit of convection for surface dew-points between 50° and 80°F was developed. Later it was discovered that SHAW had suggested that the height of the tropopause was probably determined by the upper limit of convection. In "Comparative meteorology" [v. 2, p. 138], he presents a chart showing the variation in the height of the tropopause, significant cloud-heights, and saturated precipitable water-charge at various latitudes.

Assuming the upper limit of convection adequately determined, it was then necessary to compute the relative depth of the inflow-column. Some direct relationship between the two is indicated, since it must take a greater volume of air to force convection up to 50,000 feet than it does to support convection to 40,000 feet. From an examination of typical cumulonimbus photographs and a study of F. H. BIGELOW'S [Mon. Weath. Rev., v. 36, pp. 245-250] models of a convective cell, it was determined that the vertical extent of the inflow-column represented about one-third of the total height of the convective cell. It was further assumed that the outflow at the top was confined principally to the upper third and that the central third of the convective cell represented mostly vertical motion. These relationships are illustrated schematically in Figure 3. It should be emphasized that the assumed dimensions are not typical of every convective cell but are designed to indicate a convective cell of maximum efficiency. With such a flow-model established it is a simple task to compute the amount of precipitable water which will be brought in by the inflow-layer and the amount which will be precipitated before this moist air flows out at the top. A curve of maximum possible effective precipitable water was therefore developed as a function of surface dew-point.

In discussing the simple rectangular basin in an earlier paragraph, it was pointed out that the average depth of precipitation cannot be computed as a direct function of the inflowing precipitable water since such an assumption required the moist air to leave the basin completely dessicated. To refine the computations for the ideal rectangular basin it becomes necessary to substitute effective precipitable water for total precipitable water. As a result, the amount of rain which can

occur over a basin becomes a function of the amount of effective precipitable water which can flow into the basin within a specified time. Unfortunately, not all basins are rectangular, but in most cases it is possible to fit the major portion of an actual basin within some simple geometric pattern of approximately the same area. For extremely small basins radial inflow must be considered and some adjustments have to be made in the size of the convective cell with reference to the size of the basin as well as for horizontal motion and internal distortion of the convective cell. The problems of small basins are more directly concerned with thunder-storm mechanisms which are being made part of a separate study.

The problem of estimating maximum possible rainfall for a specified basin can therefore be classified into three relatively distinct categories:

(a) Geometrical--The fitting of the basin to some simple geometric figure in order that calculation of the rates of inflow can be simplified
(b) Thermodynamical--Which combines a statistical survey of observed dew-points with consideration of the source-region of moist air for the locality in order to determine the limiting values of dew-point and effective precipitable water
(c) Dynamical--Which is concerned with the determination of the causes of extreme rates of inflow of moist air, their limiting magnitude, and the individual and combined relationships between their magnitude and duration

The geometrical problem will be discussed later in the application of the method to a specific basin. The thermodynamical problem has been discussed briefly and will be treated further under practical applications.

The dynamical problem appears to be the most difficult, and one which a theoretical, dynamic meteorologist might say is impossible. However, approaching the problem from the viewpoint of synoptic meteorology and analyzing the storms with the aid of all available data, it is soon discovered that all the major storms of record for a given locality exhibit remarkably similar synoptic patterns. Furthermore, if the storms discussed are of comparable magnitude in depth of rainfall, the significant and controlling meteorological elements are also of about the same magnitude. These elements or meteorological phenomena are lapse-rates, pressure-gradients both surface and aloft, extent and intensity of cyclonic developments and their relative position at the surface and aloft, moisture-charge and temperature-contrasts. It seems hopeless to compute the energy, rate of development, and duration of a storm from purely theoretical formulas; but by thorough analysis and identification one can establish the magnitude and relative importance of the controlling meteorological phenomena.

There still remains the problem of determining the upper limits of these phenomena from both statistical and theoretical considerations. For example:

(1) The moisture-charge in the warm air--The extreme value of this factor is determined by sea-surface temperatures in the source-region which fortunately are very conservative for their season and their locality. The modification of the moisture-charge of the air column as it moves away from the source-region can be reasonably determined by examining the modifying influences it must undergo in traveling from the source-region to the basin and also by a thorough statistical survey of extreme dew-points observed in the locality of the basin.
(2) Rates of wind-movement at the surface--This can also be adequately determined from a statistical survey of extreme and maximum winds observed at the control-station and at nearby stations of similar exposure. In most areas the significant moisture-bearing wind has a southerly component whereas the extreme wind of record has a northerly component and therefore the maximum wind to be expected with a southerly component will generally not be higher than the extreme recorded from any direction. However, there is little security in considering only the maximum observed wind for five minutes because significant storms over most basins have durations of 12 to 96 hours. A statistical comparison of observed total movement in 12 hours with observed movements for shorter and longer periods helps fix the relationship between duration and magnitude. Remembering, however, that varying depths of inflow-columns are assumed, it becomes necessary to determine limiting values of wind-velocity in the free air as well.
(3) Rate of wind-movement aloft--Major storms over large areas in the United States usually occur to the east of an intense cold cyclonic circulation aloft. The intensity of the low-pressure development which can be reasonably expected in the mid-troposphere can be estimated from a survey of temperatures at the five-km level. Such a survey is kept up-to-date for all the available soundings in the United States. Theoretical checks on the magnitude of extreme temperatures at five km can be obtained from consideration of the trajectories of polar maritime air, which is generally the type of air-mass occurring within the cold cyclonic circulation aloft. Since such an

air-mass must move over a body of water whose surface-temperature is near 0°C the extreme minimum temperature at five km, with a dry adiabatic lapse-rate, would be near -50°C and with a pseudo-adiabatic rate near -43°c. The lowest observed temperatures at five km are near -45°C in northern United States and show a gradual increase with decreasing latitude. The extreme maximum temperatures at five km during any storm-period is fixed by the surface dew-point and the pseudo-adiabatic lapse-rate in the convergent moist air. Knowing the temperature-range, the pressure-range at five km can be quantitatively determined and a reasonable, qualitative adjustment of synoptic patterns permits a quite accurate determination of the limiting pressure-gradient. A further check on the maximum winds aloft can be obtained from records of observed wind-velocities. Unfortunately this source of information is not complete because not all available data have been thoroughly organized and, furthermore, pilot-balloon data are apt to be missing for higher levels during periods of strong wind and entirely missing in the region of intense rainfall. However, records of extreme wind have been successfully used and found to be in reasonable accord with pressure-gradients estimated from theoretical and statistical observations.

(4) Distribution of wind-velocities with height--The change of wind-velocity with height is a function of the changes in density and in pressure-gradient. Density must decrease with height and tends to increase the wind-velocities. The pressure-gradient can either increase or decrease with height. For the particular basin being studied there is generally one outstanding synoptic type which can be expected to produce the maximum rainfall. From an examination of the significant air-masses involved one can usually anticipate the temperatures and lapse-rates in the cold and warm air. By plotting temperature against pressure at fixed levels on a chart such as Figure 4, showing lines of constant density, one can easily identify the direction of the density-gradient at any elevation and therefore determine directly whether or not pressure-gradient is increasing with height. Briefly, it can be stated that in order to have pressure-gradient increasing with height the center of lowest pressure must remain the center of highest density. During major storms the pressure-gradient will be so steep that it will not be possible to obtain a temperature-gradient steep enough to give higher density in the center of low pressure. Furthermore, regardless of the initial conditions of temperature and pressure at the surface and the lapse-rate in the free air, the tendency will be for the surfaces of constant density to become approximately horizontal at the nine-km level.

(5) Low pressure at the surface--Extreme minimum values of surface-pressure in the United States have been tabulated by Major BOWIE [Mon. Weath. Rev., pp. 241-242, September 1940] and serve as convenient guides for comparison with major flood-storms of record.

(6) Duration of high winds and high moisture-content--In the temperate latitudes abnormally high moisture-content is usually associated with a pronounced northward thrust of warm air accompanied, if not induced, by a pronounced southward thrust of cold air on its left. The temperature-contrast between northward-moving and southward-moving air-masses in a great measure determines the magnitude and duration of the resultant cyclonic development. Additional impetus to the cyclonic development is provided by the latent heat within the moist air. The magnitude of all three of the above elements has been previously discussed. In general the more intense the cyclonic development the stronger will be the northward-moving moisture-bearing winds and also the stronger will be the movement of the southward-moving winds which bring in dry air behind the cold front to end the rain-regime. This is merely another way of expressing the intensity-duration relationships which hydrologists had previously determined from statistical considerations.

In summary, therefore, the maximum amount of rain which can occur over a given basin is determined from the amount of moist air that can flow over the basin and the maximum amount of moisture which can be precipitated from that moist air. These functions can be determined directly or indirectly from theoretical considerations or from combined synoptic statistical studies of major storms. The maximum storm can then be computed directly or indirectly by a combined statistical and theoretical adjustment of observed major storms. Practical applications of the above methods to specific basins will be shown in the following examples.

The first example, the storm of July 4-5, 1939, over eastern Kentucky, produced the maximum rainfall over small areas in that region. To such a storm a radial-inflow equation is applicable. Trajectories and fields of motion in two layers of atmosphere computed from pilot-balloon observations were analyzed in detail. Figure 5 shows 12-hour trajectories of columns of air that were originally equidistant. Kentucky was the meeting place of two contrasting air-streams, namely, a relatively cold air-mass from the north and a broad anticyclonic moist tongue transporting convectively unstable tropical gulf air which had retained its original characteristics. Except perhaps for the intensity of convergence there is nothing particularly unusual about such a circulation-pattern. The important distinguishing feature of this storm seems to be the explosive thermodynamic state of the air in the warm sector, evidenced by soundings showing that the entire

convergence layer reached saturation at one time. Figure 6 shows the center of convergence over the rain-area. Since both the computed inflow-velocities and moisture-charge were of a magnitude comparable with the theoretical maxima, it may be assumed that this was a maximum storm.

The next example shows how the maximum possible precipitation over the Ohio River tributary basins above Pittsburgh was computed. The "Pittsburgh Basin" is roughly rectangular in shape, extending 100 miles east and west and 200 miles north and south. Since the principal moisture-inflow must be from the south, even though in the very lowest layers the winds might be southeast, the following equation for average depth over the basin was developed:

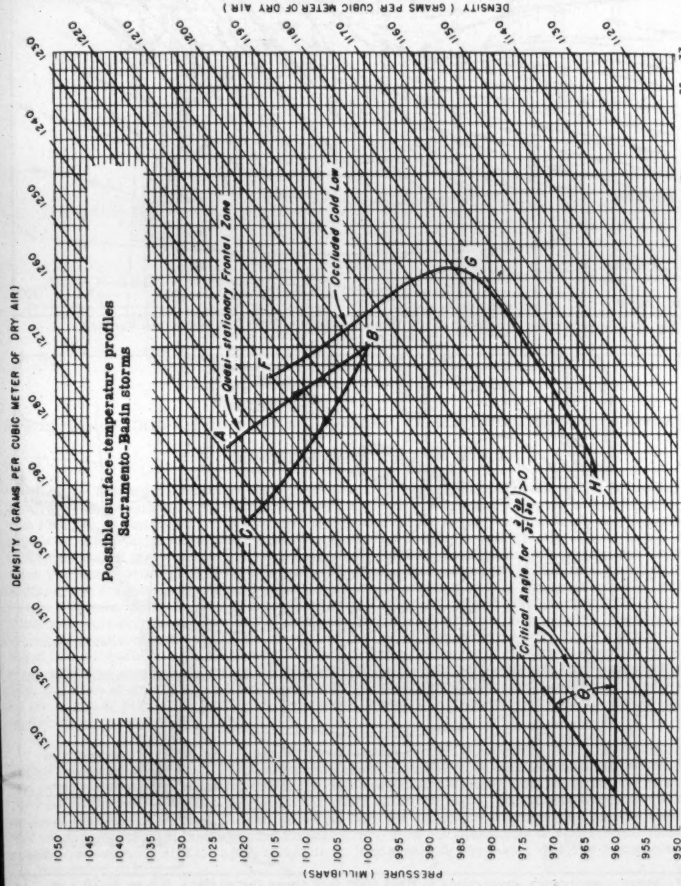

Fig. 4.--Density-chart

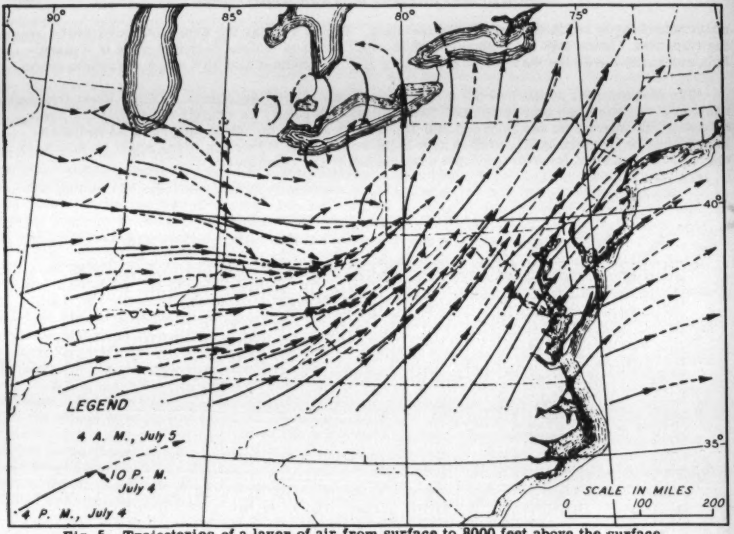

Fig. 5--Trajectories of a layer of air from surface to 8000 feet above the surface, July 4-5, 1939

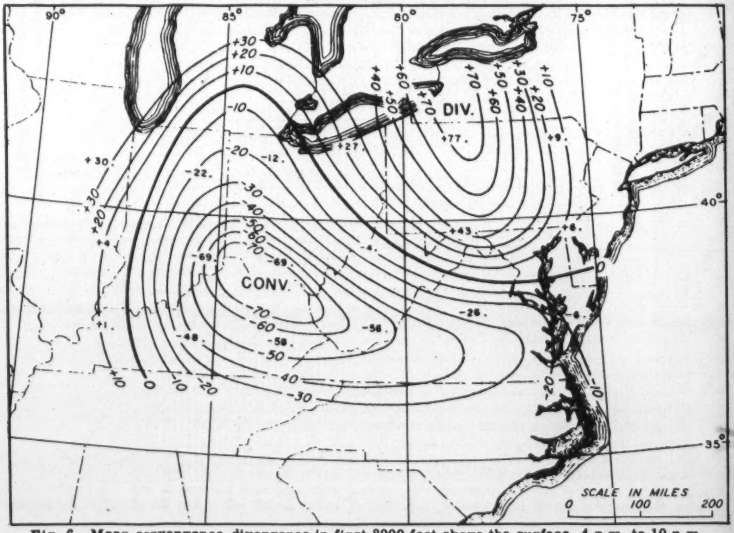

Fig. 6--Mean convergence-divergence in first 8000 feet above the surface, 4 p.m. to 10 p.m., July 4, 1939 (numbers are proportional to outflow-velocity)

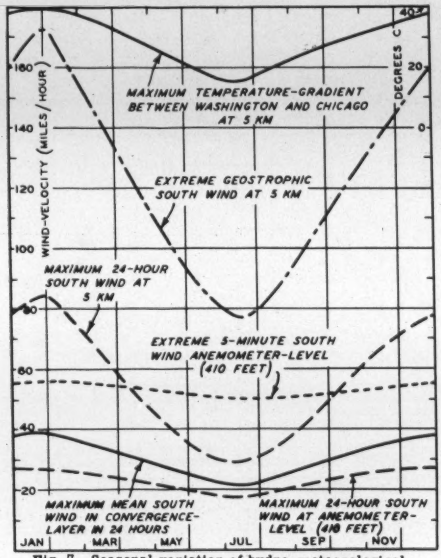

Fig. 7--Seasonal variation of hydro-meteorological factors: Maximum south winds at Pittsburgh

Average depth = [(Inflow-width × total wind-movement × effective precipitable water)/area of basin]

(Inflow-width/area of basin) = 1/200

Figure 7 shows the basis for determination of the maximum south wind in the inflow-layer. As previously mentioned, the relationship between temperature and pressure at the five-km level was found to be consistent. Thus the maximum geostrophic wind from the south was computed by assuming a maximum temperature-gradient between Washington and Chicago at that level. For a determination of the maximum south wind near the surface the Pittsburgh anemometer-records were studied in detail. Since the elevation of the anemometer at that station is 410 feet above the surface, the frictional effect could be neglected and a constant rate of change of velocity with height assumed. Based on these considerations, a seasonal curve of the maximum 24-hour south wind in the convergence-layer was developed. The maximum effective precipitable water was determined from a complete analysis of surface dew-point observations for a large number of stations in northeastern United States (see Fig. 8). From the curve of maximum wind and of maximum effective precipitable water the maximum possible rainfall-depth was then computed (see Fig. 9). It is of hydrologic interest to note that although the maximum possible rain would occur in the summer season, if snow-melt and runoff-factors are taken into account the maximum flood would occur in winter (see Fig. 10).

In computing the maximum possible precipitation for the Sacramento Basin two additional factors must be dealt with. First, the theory must be modified to take into account the effect of the orographic barrier because, obviously, some precipitable water would necessarily be deposited on the Coastal Range before the air could enter the basin. In the second place, since the critical storm is of at least 72-hour duration, both the maximum effective precipitable water and the wind-velocity must be integrated through time. It is not reasonable to assume that these elements could remain at their peak-value for so long a period. By taking stability into account,

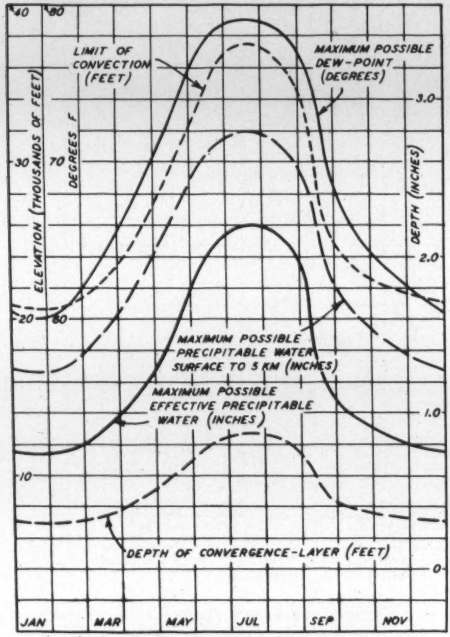

Fig. 8--Seasonal variation of hydro-meteorological factors: Maximum moisture-content, Ohio River Basin above Pittsburgh

three types of orographic rain were defined:

(a) Stable orographic rain--When the lapse-rate is less than the pseudo-adiabatic, and thus the air must be forced up the mountain slope.

(b) Incomplete convective orographic rain--When the air-mass is slightly unstable and thus possesses a convective component, but the convective process is not complete in the sense that not all the effective precipitable water is realized.

(c) Complete convective orographic rain--When all the effective precipitable water is realized; this would be the case when an unstable column undergoes extreme convergence; the rainfall would be the same as in the non-orographic convective process, the mountain merely acting as a trigger in setting off the convection.

The heights to which the bases of columns would have to be lifted in order to enter the basin from any given direction were integrated through the inflow-widths by means of topographic charts. These were called effective heights. Obviously, the amount of moisture-inflow from a given direction is a function of the effective heights from that direction. Basin-constants were computed for various combinations of orographic rain and the most critical assumption was found to be incomplete orographic rain to the west of the basin and complete orographic rain within the basin, the most critical inflow-direction being southwest. Figure 11, which is a synoptic chart of

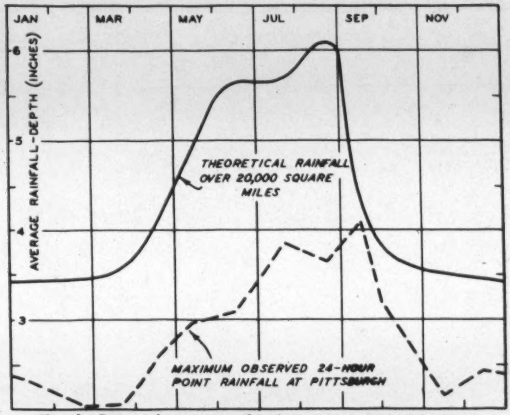

Fig. 9--Seasonal variation of hydro-meteorological factors: Computed maximum possible average rainfall-depth in 24 hours over the Ohio River tributaries above Pittsburgh

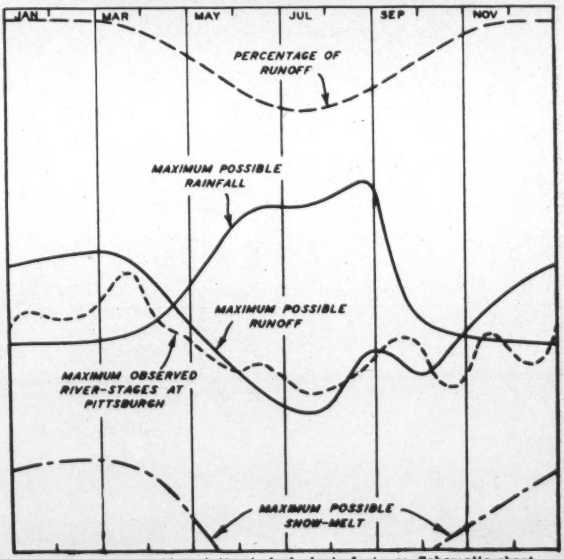

Fig. 10--Seasonal variation in hydrologic factors: Schematic chart

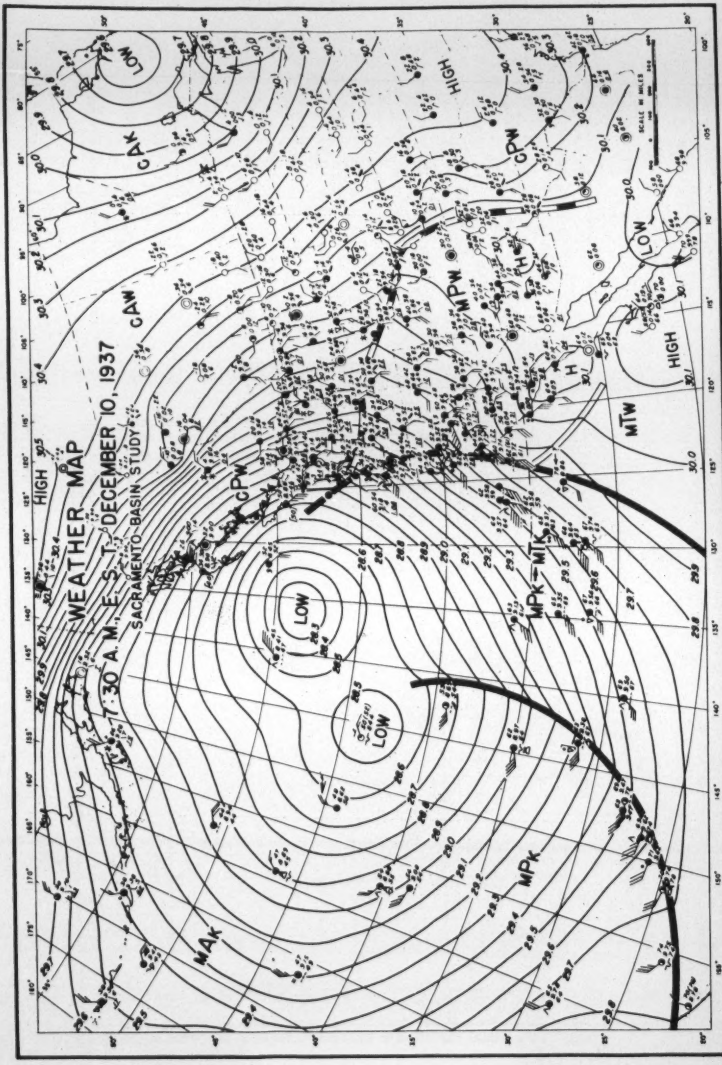

Fig. 11.--Weather-map, $7^h\,30^m$ a.m., EST, December 10, 1937, Sacramento Basin study

the storm of December, 1937, during its fullest development, illustrates the critical pattern.

The assumption is that the air as it flows inland is saturated and slightly unstable. Originally Polar Pacific, it has been rendered unstable and moistened in its lower layers by a long passage over warm Pacific waters. In the last part of its journey over the Pacific, however, it has been stabilized near the surface by the cooler waters off the California Coast. Passing inland as a southwest current, it crosses the Coast Range, depositing incomplete convective rain. Because of the triangular shape of the valley-floor the air in the lowest 1,000 feet, which can enter only through the Golden Gate, is forced to undergo horizontal convergence in two ways: First, the wind is constrained to a more southerly course, thus acquiring a greater cyclonic vorticity; second, as the air flows toward the apex of the triangle, it has less and less horizontal space. Both of these effects are compensated for in part by vertical stretching. The vertical motions cause decreasing stability to greater and greater heights until finally convective overturning takes place. In the early stages of this process there is usually a layer of cold air hugging the valley-floor which is eventually forced up the mountain slope at the northern part of the basin and from which stable orographic rain results.

Having computed basin constants for every inflow-direction based on these assumptions, a method was devised for testing their validity. The following equation was used:

$$R = \int f v dt$$

where R is average depth of precipitation over the basin, f the moisture-index which is a function of dew-point and inflow-direction, and t time. Using Point Reyes wind-data and dew-point data from San Francisco, Mount Tamalpais and Donner Summit, when available, the average depths of rainfall were computed for several major storms. The values thus obtained were then compared with those computed from isohyetal charts based on rainfall-observations. This is shown in Figure 12, where, except for the points near the bottom of the chart, the line of perfect agreement shows a very good fit. Those points, however, represent rainfall of short duration which cannot be too reliably determined. It will be noted that some of the scatter is due to the non-representativeness of the dew-point index-station. For example, the highest circle and triangle on the chart are for the same storm, indicating that the dew-points at Donner Summit were in this case a more reliable index than those at San Francisco. An attempt was also made to compare the time-distribution of intensities. Figure 13 shows the result of this test for the storm of February, 1940, for which there was the greatest amount of autographic rainfall-data.

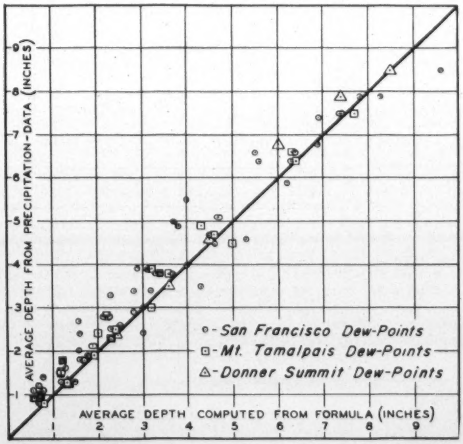

Fig. 12--Average precipitation-depths over total basin

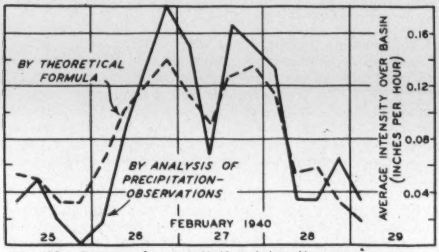

Fig. 13--Computed precipitation-intensity, average over total basin, storm of February 25-29, 1940

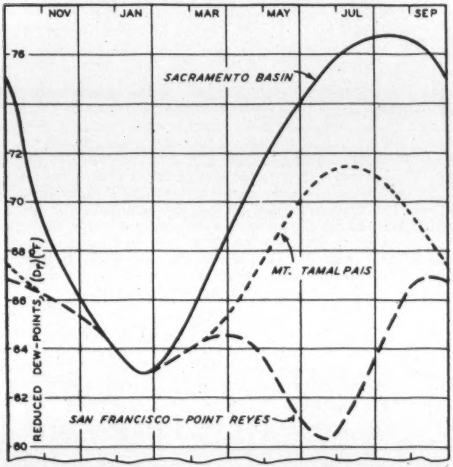

Fig. 14--Seasonal variation of maximum reduced dew-points

A survey was made of the maximum dew-points for all months at a number of stations in and near the Sacramento Basin. It was found that after reducing these to 1,000 millibars, three composite seasonal curves could be drawn (Fig. 14). For reasons which are discussed in the Sacramento Report, it was decided that only that portion of the chart where the three curves are concurrent could be considered pertinent to the dew-points of the maximum possible storm. Figure 15, based on the observed behavior of representative dew-points in major storms, shows how the average moisture-index varies with duration. The maximum wind-velocity in the inflow-layer and its duration-curve were determined from the anemometer-records at Point Reyes, San Francisco, and several other stations, from pilot-balloon observations, and from a consideration of the possible variation of pressure-gradient with height. The following empirical formula for variation of wind-velocity with height in the inflow-layer of the maximum storm, neglecting friction, was developed:

$$v = v_0 (1 + 0.06z)$$

where v is the velocity in miles per hour, v_0 the velocity at some fixed elevation, and z the height in thousands of feet above the fixed elevation. Figure 16 shows the duration-depth curve of the

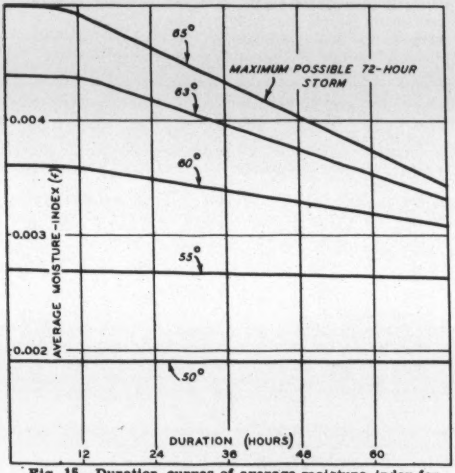

Fig. 15--Duration-curves of average moisture-index for various maximum dew-points

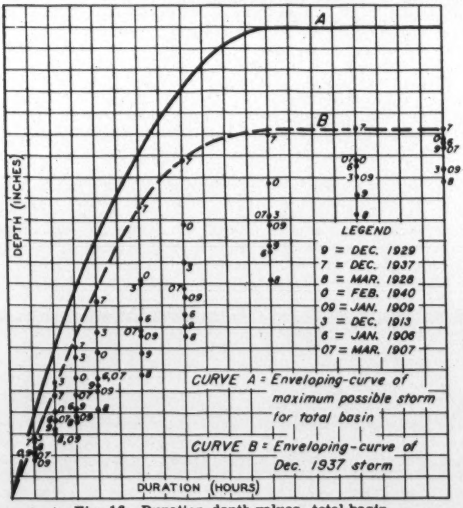

Fig. 16--Duration-depth values, total basin

maximum possible storm computed from the duration-curves of maximum moisture-index and wind-velocity. If the storm of December, 1937, is a meteorological model of the maximum 72-hour storm, the final computations imply that this storm could have been 13 per cent greater on account of dew-point increase and 14.5 per cent greater on account of increased wind, a combined increase of 29 per cent.

The investigations discussed herein are being conducted by the Weather Bureau for and under an allotment of funds from the Engineer Department, Corps of Engineers, United States Army.

The authors are indebted to the staff of the Hydrometeorological Section for much of the material used in this paper, and in particular to A. L. SHANDS for carefully editing the text.

The bibliography appended to "A report on the maximum possible precipitation over the Sacramento Basin, California" is applicable to this paper. The present intention is to publish the report in the near future.

U. S. Weather Bureau,
Washington, D. C.

ON THE OBSERVATION AND MEASUREMENT OF THE APPARENT SHIFT IN DIRECTION OF THE RADIO BEAM OF AN AIR-BEACON AND CERTAIN RELATIONS TO METEOROLOGICAL CONDITIONS

H. T. Stetson and D. S. Mackiernan, Jr.

Daily observations of the relative field-strengths of two adjacent quadrants of the southwest leg of the Boston Radio Air-Beacon have been received at the Cosmic-Research Laboratory at Needham since March, 1941. The location of the Laboratory is near the northwest edge of the twilight band, ten miles distant from the sending beacon (Fig. 1). As is generally known, the antenna-system of an air-beacon is arranged to send the Morse-Code letter A from a pair of opposite towers and the Morse-Code letter N from a second pair of opposite towers whose direction is usually at right-angles to the directional system of the first pair. The overlapping field-pattern results in a continuous hum in the direction in which the two code-letters overlap. This is known as the "on-course" beam. Near the edge of the twilight band the signal of one of these letters dominates over the other, and in the case of the Needham Laboratory this is the A-signal. The direction of the axis of the beam may be judged from the ratio of the intensities of the A- and N-signals received. An observed change in the ratio of the relative strengths of these signals may be considered as equivalent to an apparent change in the azimuth of the beam. These ratios have been used to study such variations as occur and to endeavor to discover whether or not such changes as may be observed bear relationship to atmospheric and meteorological conditions at the time.

To interpret ratio-changes in terms of apparent azimuth deviations a survey was made at right-angles to the beam in the vicinity of the Laboratory for two miles either side of the axis. A plot of the ratios against the known bearing of the Beacon at the several stations occupied has served to interpret (A/N)-ratios in terms of degrees of azimuth. Three diagrams (Figs. 2, 3, 4) show the oscillations of the (A/N)-ratio for March, 1941, to March, 1942. A study of this graph shows little evidence of any preferential change with the occurrence of rain, but marked evidence for an apparent increase in azimuth of the direction of the beam from the receiving station with heavy snowfall, barring one exception. The greatest departure was observed on January 4, 1942, when during the peak of a heavy snow-storm the (A/N)-ratios indicated the observed beam to have increased its azimuth by 7° with a subsequent recovery to normal five to six hours after the maximum deviation had occurred. It has been in general assumed that such deviations during snowfall have been brought about through an accumulation of snow on the insulators of the antenna-system at the air-beacon calling for constant vigil and prompt removal of snow during storm-periods. The lack of any evidence of a sudden recovery after snow-removal leaves this explanation open to question.

In addition to the sporadic variations noted on the graph, a general trend in the curve has persisted of an apparent annual or seasonal nature. This is best shown by taking monthly averages. Figure 5 illustrates the yearly variation observed from March, 1941, to March, 1942, when these monthly averages have been smoothed by running means. The inference of the curve is that a difference in direction may amount to more than 1° in mid-summer as compared with spring. Whether or not the cause of this is a seasonal meteorological change or is due to systematic

changes in the conductivity of the ground or of the lower air remains to be determined.

While it is difficult to say how the ground-waves can in any way be affected by ionospheric disturbances, it is to be noted that one of the most abrupt changes in (A/N) on record occurred May 28-June 6, 1941, a period including a major ionic storm.

The desirability of continuous hourly readings for 24 hours of each day led to the design and construction of a special apparatus to make possible the automatic recording of the relative field-intensities of the two quadrants concerned. The apparatus is designed to permit the recording of

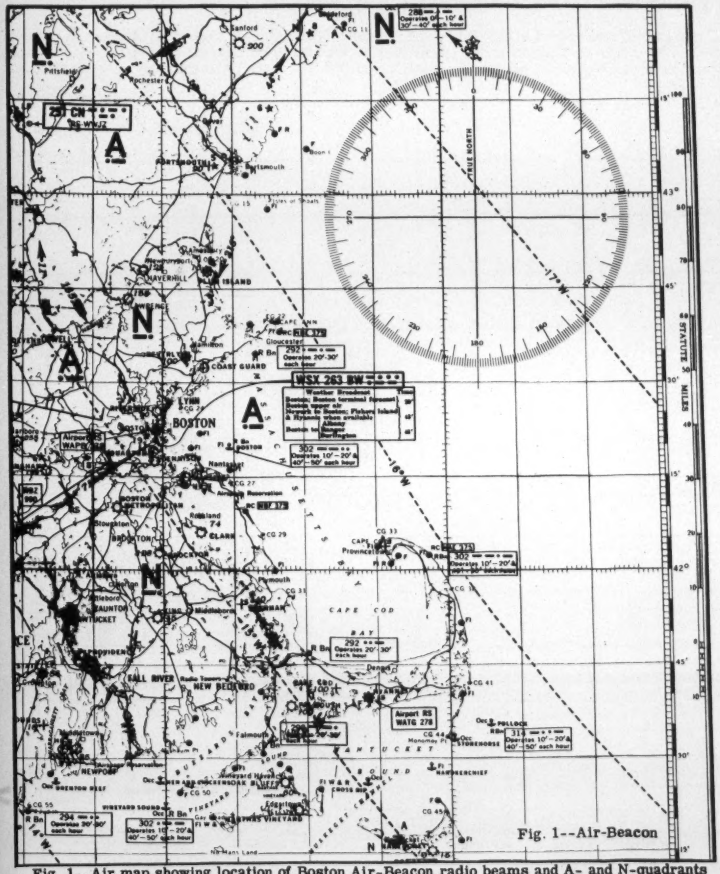

Fig. 1--Air map showing location of Boston Air-Beacon radio beams and A- and N-quadrants (Recorder located on northwest edge of 71°-beam 10 miles from Beacon)

these signals on a standard strip-chart recorder (in this instance a Leeds and Northrup Micromax (Fig. 6). The apparatus is built in two sections, (1) a separator for separating the A- and the N-signals, and (2) a storage means for storing the separate A- and N-signals for a sufficient period to enable the Micromax recorder to reach a balance.

The Micromax recorder cannot be connected directly to the radio receiver, as is done in conventional field-strength recorders, since its speed of response is much too slow to respond to the individual A- and N-signals, since the signals are transmitted at the rate of 24 characters per minute. Even if the recorder could respond to this rate it would require an excessively high chart-speed to separate the individual signals. Therefore, some method of separating and storing the A- and N-signals is required.

The method employed for separating the A- and N-signals is the following. A disk is arranged to rotate, by means of a synchronous motor, at the rate of 24 revolutions per minute. On the periphery of the disk is placed a projection about one-eighth inch high. Diametrically opposite the pro-

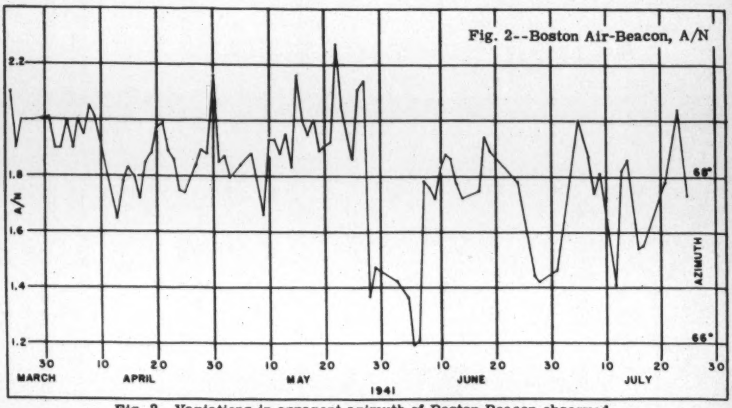

Fig. 2--Variations in apparent azimuth of Boston Beacon observed at Needham, March, 1941, to July, 1941

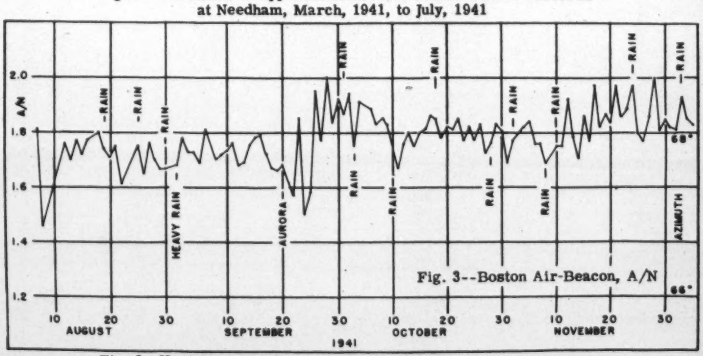

Fig. 3--Variations in apparent azimuth of Boston Beacon observed at Needham, August, 1941, to November, 1941

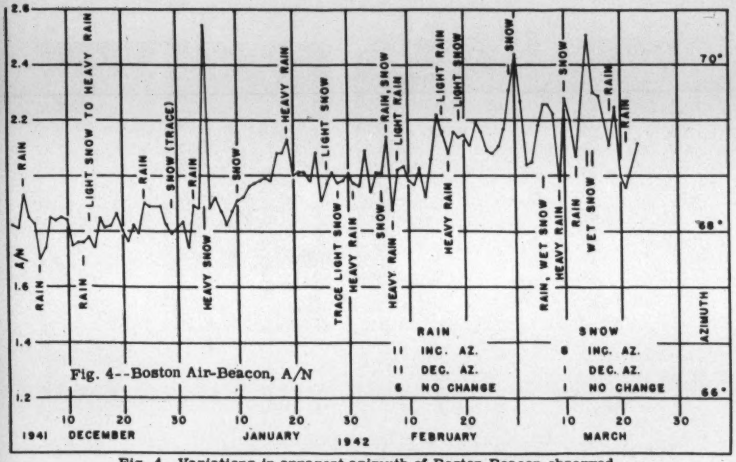

Fig. 4--Boston Air-Beacon, A/N

Fig. 4--Variations in apparent azimuth of Boston Beacon observed at Needham, December, 1941, to March, 1942

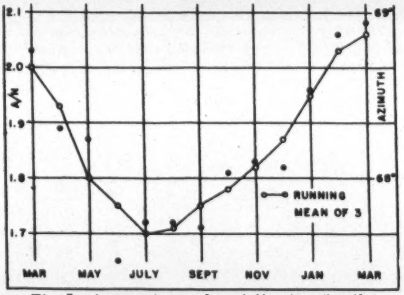

Fig. 5--Apparent annual variation in azimuth March, 1941, to March, 1942

jection a notch one-eighth inch deep is cut into the disk. An arm carrying two contacts is arranged to bear against the edge of the disk. One of these contacts is closed by the passage of the projection under the contact-arm, the other by the passage of the notch. The duration of the contact in each case is about one second. By proper orientation of the contact-arm about the edge of the disk it is possible to make one contact occur during the dash of the A-signal, and the other during the dash of the N-signal. These contacts may be used to switch the output of the receiver from the A- to the N-storage system and back at the proper intervals. The storage of the A- and N-signals is effected as follows. After being amplified, the signals from the receiver are rectified by means of a vacuum-tube rectifier. The output of this rectifier is switched alternately from the A- to the N-storage system. The switching is done by relays controlled by the selector-disk contacts.

The A- and N-storage systems are identical and consist of a six-mfd condenser shunted by a 21-megohm-resistor network. After a short period of operation the potential, which each con-

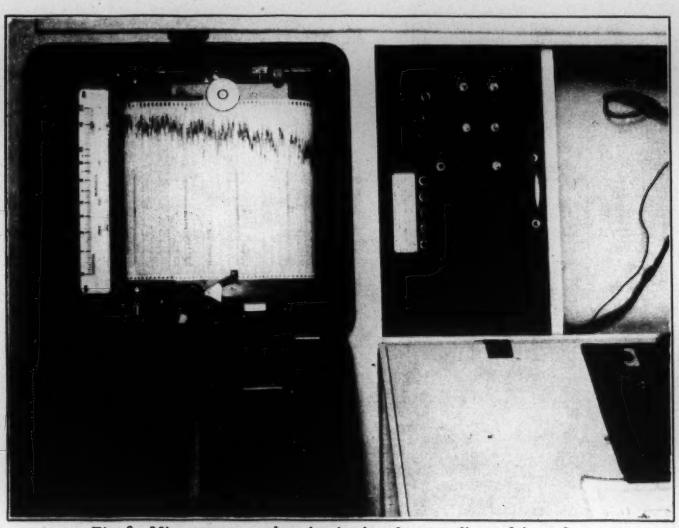

Fig. 6--Micromax recorder showing hourly recordings of A- and N-signals (Irregular recorded band at right represents field-intensities of another station; control-panel for (A/N)-recorder is shown below record)

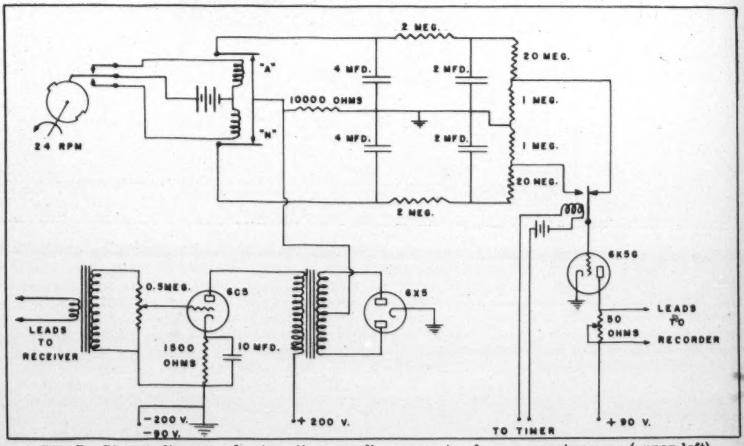

Fig. 7--Circuit-diagram of automatic recording apparatus from separator-cam (upper left) to leads to recorder (lower right)

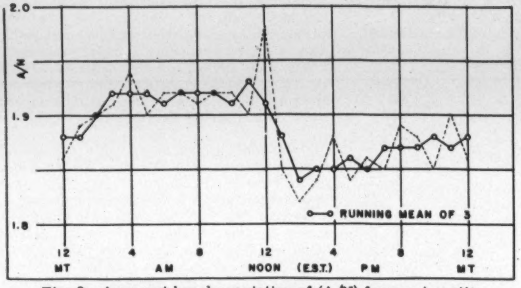

Fig. 8--Apparent hourly variation of (A/N) from automatic recorder, March 13 to March 25, 1942

denser assumes, becomes constant and proportional to the rectified signal which charged it. The potential of either condenser is measured by a vacuum-tube voltmeter, which is switched automatically from one condenser to the other by means of a relay and time-clock. The recording galvanometer is connected in the plate-circuit of this vacuum-tube voltmeter. The circuit is illustrated by Figure 7.

The apparent diurnal variation of the (A/N)-ratio has indicated an apparent wandering of the azimuth of the beam during the interval March 13 to March 25 as shown in Figure 8. It would appear that there is a gradual rise to a maximum during the forenoon with an abrupt drop through the noon interval to a sub-average value during the afternoon after which normal intensity for the day is recovered. The character of the curve resembles somewhat that of the known curve of diurnal variation in the magnetic field of the Earth at this latitude.

It is proposed to continue these recordings so long as it is feasible in order to determine more definitely the relation between atmospheric, electric, and meteorological changes at the Earth's surface and the apparent changes in the (A/N)-ratios observed.

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THE INTERDIURNAL VARIABILITY OF TEMPERATURE ON MOUNT WASHINGTON

V. Conrad

In two recent papers I dealt with the aperiodic changes of temperature on Mount Washington [see 1 of "References" at end of paper]. The present investigation is a continuation of the former attempts.

The first problem in the range of variability of an element considers the variations to which the average values are subject. The second task is to investigate the variations from day to day. These are called interdiurnal variations. Finally the relations between the general variability and the interdiurnal variability are important. For studying the general variability a rather long series of observations is necessary; so it seemed better to begin with an investigation in the interdiurnal variability. The three-year temperature-tables (1935 to 1937) of the Mount Washington Observatory (altitude 6,270 feet) could be used again.

Usually the interdiurnal variability is defined by the difference between the mean temperature of a day and that of the next day. Here another method is chosen, namely, the difference between the temperatures at 5 a.m. and 2 p.m. of consecutive days. The advantage of this method is above all a practical one. It is not necessary to calculate daily means. Also from the standpoint of statistics sometimes the differences between the temperatures at fixed hours yield a better picture of the variability than the differences between the daily means. If the duration of the increasing

Table 1--Frequencies of "warmings" and "coolings" ≥ 20°F, Mount Washington, 5 a.m., sums for years 1935-37

Month	Warmings	Coolings
January	5	11
February	4	6
March	6	5
April	1	3
May	1	2
June	..	1
July	..	..
August	..	..
September	..	3
October	1	6
November	1	4
December	4	4
3 years	23	45

and of the following decreasing trend is about 48 hours or shorter, then it is possible that even great variations of temperature are not indicated by consecutive daily means. In this respect the differences between fixed hours seem to be more advantageous. Starting from the above hours one gets the diurnal variability for a time which lies close to the minimum on one hand and to the maximum on the other [2].

However, a difficulty occurs if the results of the fixed-hour method and those of the usual daily-mean method are to be compared. Because data of the United States were not at hand, Central European data [3] were used to get an estimate as to how far a comparison of the results obtained by the two methods would be possible. This sampling shows that the 5a-variability is three per cent smaller than the daily-mean variability and the 2p-variability is ten per cent greater. If it is assumed that these results are valid also for Mount Washington, the 5a-variability at this place can be compared with the variability at another place, based on the daily mean.

Table 1 shows in a rough but clear way some characteristic features of the diurnal variability of temperature on Mount Washington. Here only frequencies of differences from day to day at 5 a.m. are considered, equal to or greater than 20°F (11°C). The choice of this threshold shows above all that the absolute amounts of the variability are very great at the summit of Mount Washington. A comparison with the analogous results [4] for Green Harbour, Spitsbergen, indicates that the variability on Mount Washington is also exceedingly high relative to other places, the location of which would also favor great variabilities. In so far as the interdiurnal variability would be caused by the temperature-effect of different air-masses only, the geographical position of Green Harbour on the coast of a glaciated island in 78° north, bordered by a relatively warm sea, would point to an especially great variability. In Green Harbour 21.6 variations of temperature from day to day ≧ 18°F occur in an average year and on Mount Washington 22.7 ≧ 20°F. The following results also show that the interdiurnal variability of temperature at Mount Washington is very great and it is to be classed as one of the greatest on Earth as far as observations exist today.

On the other hand, the numbers in Table 1 indicate that the great warmings and coolings are phenomena of the cooler portion of the year (increasing temperature from one day to the next is called "warming", decreasing "cooling"). In three summers no warming ≧ 20°F occurred and only one cooling.

The annual marches of the average and extreme values for 5a and 2p, warmings and coolings separately, are to be seen from the first part of Table 2, where the values for the seasons are also indicated. The second part of Table 2 contains the interdiurnal variability irrespective of sign and the third part gives the ratios (c/w), that is, the ratio of average cooling to average warming for the months. Because only three years of observations are used, it is not surprising that the annual march of the ratios shows rather great irregularities. Therefore, the series were smoothed with the formula [(a + 2b + c)/4].

On Mount Washington the interdiurnal variability, irrespective of sign, is 11°.4 F in January while at Green Harbour it is 9°.2 F. At the latter station the greatest warming within five years was 38°.2 F and the greatest cooling 31°.1 F. On Mount Washington the corresponding values were 42°F and 54°F. Thus Mount Washington has excessive temperature-variations from one day to the next. The remarkable fact to be emphasized is that on the coast of Spitsbergen warmings are much greater than coolings while this relation is the reverse on Mount Washington. To my knowledge the average values of the interdiurnal variability on Mount Washington are surpassed only on the Barrier of the Antarctic Continent. There at Framheim (the winter quarters of ROALD AMUNDSEN in 1911 before he reached the South Pole) the interdiurnal variability was 15°.3 F in July and August, and the greatest average monthly warming and cooling were 17°.0 and 14°.5 respectively [5]. The interdiurnal variability of other places at the coast of the Antarctic Continent is rather less than that of Mount Washington. At Framheim warmings also exceed coolings.

Disregarding some irregularities caused by the shortness of the period of only three years, there is a strongly marked annual march of the interdiurnal variability, with a high maximum in

Table 2--Interdiurnal variability of temperature, °F, Mt. Washington, New Hampshire, average and extreme values for years 1935-37

Month, season	Warmings				Coolings			
	Average values		Maxima		Average values		Maxima	
	5 am	2 pm	5 am	2 pm	5 am	2 pm	5 am	2 pm
Jan.	9.6	10.8	30	42	13.8	13.0	34	39
Feb.	10.4	9.9	30	27	9.9	12.1	54	28
Mar.	9.2	9.1	29	31	10.4	10.4	50	32
Apr.	5.9	6.0	24	16	6.6	6.8	37	25
May	5.6	6.6	22	23	6.4	8.1	22	31
June	5.0	4.7	15	15	5.2	4.9	21	14
July	3.7	4.1	9	15	4.4	5.3	19	20
Aug.	4.1	4.7	12	14	4.4	4.4	17	18
Sep.	5.2	6.2	17	20	7.5	6.4	26	27
Oct.	7.7	6.7	20	16	8.3	9.5	32	30
Nov.	7.5	8.3	19	21	8.5	9.3	27	32
Dec.	8.3	8.8	27	29	9.2	9.7	34	27
Year	6.8	7.2	21	22	7.9	8.3	31	27
Winter	9.4	9.8	30	42	11.0	11.6	54	39
Spring	6.9	7.2	29	31	7.8	8.4	50	32
Summer	4.3	4.5	15	15	4.7	4.9	21	20
Fall	6.8	7.1	20	21	8.1	8.4	32	32

Table 2-A--Interdiurnal variability, irrespective of sign

Hour	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F
5 am	11.4	10.1	9.8	6.2	5.9	5.1	4.0	4.2	6.3	8.0	8.0	8.7
2 pm	11.8	10.8	9.7	6.3	7.2	4.8	4.6	4.5	6.3	7.9	8.8	9.2
Year: 5 am, 7.32; 2 pm, 7.87												
Ratio, c/w (smoothed)												
5 am	1.09	1.06	1.08	1.13	1.10	1.10	1.10	1.19	1.26	1.19	1.10	1.11
2 pm	1.19	1.20	1.16	1.16	1.16	1.14	1.13	1.04	1.11	1.25	1.19	1.13

January or in February and a deep minimum in July or in August. The average monthly values of warmings and coolings are correlated in the strongest way. I have found for the 5a-variability $r = +0.905$ with a probable error of ± 0.035. This fact seems to be very important and shows that the intensity of warmings as well as of coolings is steered not by local factors but by the general circulation.

The ratio between average monthly coolings and warmings is subject to rather small variations in the course of the year, except during September and October, in which months the ratio (c/w) reaches a steep maximum both in the case of 5a-variability and in that of 2p-variability. This result is in best agreement with the facts I could derive from the distribution of the extremes of temperature over the 24 hours of the day [1, p. 297] for Mount Washington for which I derived a curve representing the annual course of the ratio between the number of days with the advection of cold air and that with the advection of warm air. The trend of this curve with its accentuated maximum in September leads to the concept of a quanta-like process which causes the cooling in fall. This idea is verified by the present investigation.

The diurnal variation of average coolings and warmings was examined also. Seemingly the variability is somewhat higher at 2 p.m. than in the early morning. The effect of incoming radiation and the more instable state of the atmosphere could make this result understandable. However, it does not appear to be certain, because the material here considered is not extensive enough.

The data of the Tables of interdiurnal differences of temperature made it possible to compute a kind of temperature-balance between the coolings and warmings for each month. The trend of the resulting curve (Fig. 1) shows that the balance is positive from the beginning of March to the beginning of August. Afterwards the curve crosses the zero-line and the greatest negative balance occurs in September, which is again in good agreement with the concept, mentioned above, of the quanta-like process of the cooling of the atmosphere in fall as far as can be shown by the observations on Mount Washington.

The curve of Figure 1 shows smoothed monthly averages; the original averaged values are -14, -3, +4, +15, +2, +1, +10, +3, -31, -2, -16, and -5 for the 12 months January to December, respectively. These numbers are valid for an average year. The balance of the whole year is negative, -37° F. This amount is very small if it is considered that this represents only a deficit of 0°1 F per day which would have to be compensated in order to maintain an invariable temperature-level from year to year.

However, these conditions could be regarded from another hypothetical standpoint. One could think that something more than three years, say perhaps 3-1/2 years, would be a sort of compensating time for the general circulation. Three and one-half years represents a well-known periodicity [6]; the physical sense of this periodicity is perhaps the compensating time of the general circulation of the atmosphere. Further investigations should test it.

For the sake of completeness it may be remarked that the interdiurnal variability of temperature on Mount Washington is about 20 per cent greater than that at the Blue Hill Observatory (altitude 635 feet) in July and 70 per cent greater in January.

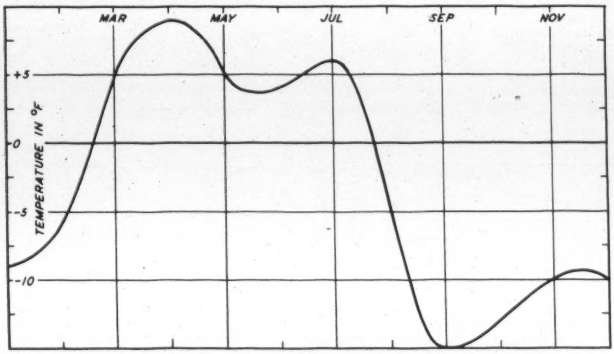

Fig. 1--Temperature-balance computed from coolings and warmings (5 a.m.) on Mount Washington in an average year

Finally, frequency-statistics have been made of the numbers of consecutive days with increasing (i) and decreasing (d) temperature, respectively. The results are presented in Table 3. The longest periods were nine days of increasing temperature and eight days of decreasing temperature. It is to be remarked that this is based on the assumption that a negative difference between the temperature at a certain hour of one day and that at the same hour of the preceding day indicates a decreasing temperature and vice versa. The variations of the temperature at other times between these given hours are disregarded.

On the average for the year, the mean duration of the increasing temperature amounts to 2.11 days, that of decreasing temperature to 1.86 days; the ratio between these two durations is 1.14 and does not vary much in the course of the year. It is remarkable that the average periods of increasing temperature are longer than those of decreasing temperature in each month. The average monthly numbers show no real annual course.

However, there is a very important fact. The lengths of the average monthly periods with increasing and decreasing temperature are strongly correlated. The correlation-coefficient is high, namely, $r = +0.7738$, and moreover the probable error, ± 0.07812, is only a tenth of the correlation-coefficient. This result is derived from the 5a-variability. The 2p-variability, subject to much more disturbance, shows similar behavior in the same sense but is not so well and clearly accentuated.

The correlation mentioned, should it hold for longer series of observations, is important to knowledge of the mechanics of air-masses. The long-range forecaster should be also interested

Table 3--Average and extreme numbers of consecutive days with increasing and decreasing temperature, average length of temperature-surges

Month, season	Averages				Maxima				Length of temperature-surges, days	
	Increasing		Decreasing		Increasing		Decreasing			
	5 am	2 pm	5 am	2 pm	5 am	2 pm	5 am	2 pm	5 am	2 pm
Jan.	1.86	1.66	1.44	1.51	5	5	4	4	3.30	3.17
Feb.	2.45	2.23	2.36	1.64	4	5	8	3	4.81	3.87
Mar.	1.92	2.39	1.79	1.67	6	4	3	3	3.71	4.06
Apr.	2.13	2.00	1.62	1.41	9	3	4	3	3.75	3.41
May	2.13	2.04	1.79	1.60	4	4	4	3	3.92	3.64
June	1.95	1.61	1.79	1.61	5	4	5	4	3.74	3.22
July	2.13	2.20	1.74	1.64	7	7	3	4	3.87	3.84
Aug.	2.40	1.84	2.05	1.87	6	4	8	6	4.45	3.71
Sep.	2.13	2.09	1.87	2.00	4	6	4	4	4.00	4.09
Oct.	2.23	2.50	2.09	1.90	4	5	6	4	4.32	4.40
Nov.	2.04	1.78	1.96	1.66	6	4	6	4	4.00	3.44
Dec.	1.92	2.36	1.84	2.00	4	5	4	4	3.76	4.36
Year	2.11	2.06	1.86	1.71	9	7	8	6	3.97	3.77
Winter	2.03	2.04	1.84	1.69	5	5	8	4	3.87	3.73
Spring	2.05	2.05	1.74	1.55	9	4	4	3	3.79	3.60
Summer	2.16	1.87	1.85	1.70	7	7	8	6	4.01	3.57
Fall	2.10	2.09	1.97	1.84	6	6	6	4	4.07	3.93

in this problem because the correlation could be valid also for fractions of a month.

At Blue Hill Observatory the lengths of the periods with increasing and with decreasing temperature are absolutely independent of one another as shown by the value of the correlation-coefficient, $r = -0.07$, with a probable error of ± 0.19. This is an indication that the high correlation mentioned is valid for the free atmosphere. The summit of Mount Washington overtops the disturbed surface-layers and its meteorological conditions are more like those of the free atmosphere in many respects. A three-dimensional synoptical examination of the cold and warm waves on Mount Washington would probably yield a physical explanation of the correlation of the lengths of periods of increasing and decreasing temperature.

In conclusion, attention may be directed to the two last columns of Table 3, which combine the average lengths of periods with increasing temperature with those of decreasing temperature. This connection yields the lengths of temperature-surges which pass the summit of Mount Washington. The mean length of a surge for the year is four days, so that about 90 surges cross the mountain range annually. The same order of magnitude was found [7] for the summit of the Sonnblick (altitude 10,190 feet). This agreement argues in favor of the reality of the phenomena here discussed and of the comparability of the methods of fixed-hour variability and daily-mean variability. This agreement supports the hypothesis that the features of interdiurnal variability observed on isolated summits are independent of the locality on the Earth's surface and more or less characteristic for the free atmosphere.

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THE SUNSPOT-PERIOD AND SPRING RAINFALL IN THE UNITED STATES

H. Helm Clayton

The publication by the Weather Bureau [p. 2, Weekly Weath. Crop Bull., March 17, 1942] of the percentage of spring precipitation in each State for every year from 1892 to 1941 gives data in a convenient form for a study of the sunspot-period in the rainfall of the different States.

In making this study, the percentages of the normal precipitation were tabulated, as in Table 1, for Arizona, South Dakota, and Florida, beginning in each case with the year of sunspot-minimum and running for 11 years.

These tabulations show that in certain States, for example, Arizona and Minnesota, the average percentages of normal precipitation at sunspot-maximum were decidedly above normal while at sunspot-minimum the percentage of precipitation averaged below normal. In other States, for example, Florida (Table 3), this condition was reversed. The States showing the largest excess of precipitation at sunspot-maximum are found in two groups, one the Central States and the other the Rocky Mountain States; those showing an inverse relation were near the Atlantic Coast.

The means for these four groups are plotted in Figure 1, together with the means of the simul-

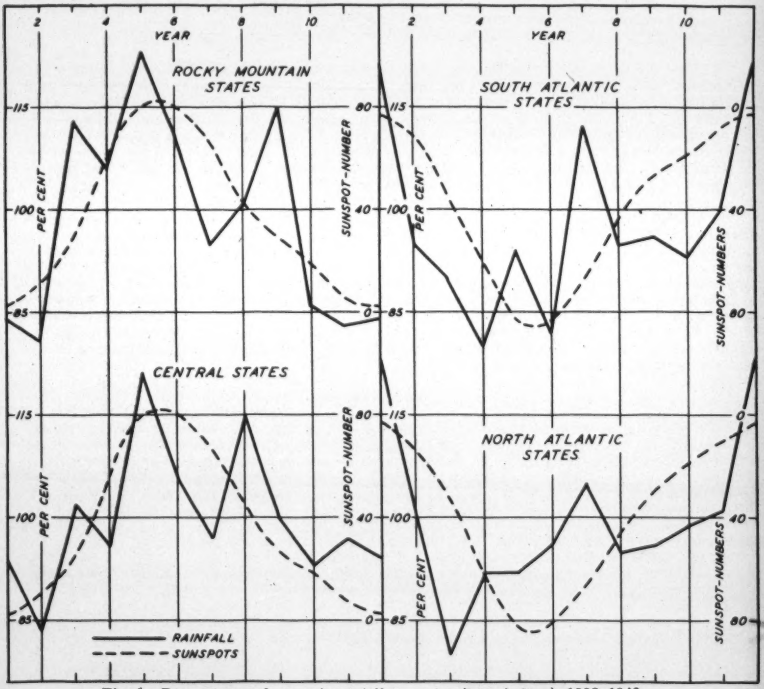

Fig. 1--Percentages of normal rainfall in spring (March-May), 1892-1940 during sunspot-period (dotted curves, sunspot-numbers)

Tables 1-4--Percentages of spring precipitation during each year of sunspot-periods, 1892-1941

Year minimum spots	Year of sunspot-period										
	1	2	3	4	5	6	7	8	9	10	11
					1--Arizona						
1889	....	....	....	120	148+	70	36	40	52	86	18*
1901	65	57	94	44	362+	158	133	103	84	50*	74
1913	36*	62	155	104	155+	104	119	110	70	121	91
1923	91	125	97	292+	99	51	69	178	89	48*	56
1933	56*	78	129	72	116	134+	64	69	310+	....	....
Mean	62	80	119	126	176+	103	84	100	121	76	60*
					2--South Dakota						
1889	....	....	....	175+	117	103	97	123	96*	107	125
1901	67	111	100	72	125	143	95	121	105	66	64*
1913	107	108	120	116	120	122+	108	160	95	96	78*
1923	78	54	57	54	179+	52*	115	93	65	119	111
1933	111	35*	128+	62	90	119	59	81	99	....	....
Mean	91	77*	101	96	126+	108	95	116	92	97	95
					3--Florida						
1889	....	....	....	41*	118+	54	115	59	89	42	65
1901	118+	81	108	59*	120+	113	89	67	98	56	88
1913	107	56	100	70	62*	106	142+	126	96	108	136
1923	136+	124	90	116	46*	157+	119	147	128	110	138
1933	138	142+	91	96	127	73*	109	83	95	....	....
Mean	125+	101	97	77*	95	101	115	96	101	80	106
					4--Sunspot-numbers						
1889	....	....	....	67	80+	79	67	41	27	26	12
1901	5*	5	18	40	48	59+	52	49	30	14	11
1913	1*	9	38	71	95+	77	67	39	27	25	4
1923	4*	11	31	55	81+	81	54	37	27	13	5
1933	5*	12	21	69	100	105+	97	66	....	....	....
Mean	4*	9	27	60	81+	80	67	46	28	19	8

*Minimum value. +Maximum value.

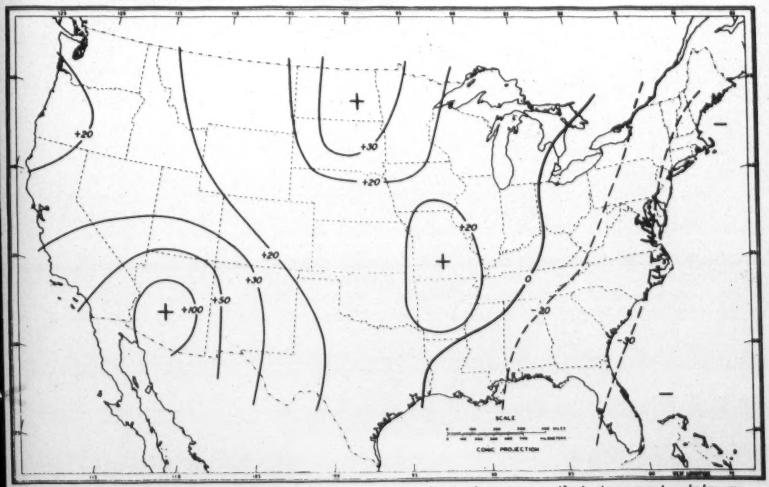

Fig. 2--Percentage of excess precipitation at sunspot-maximum over that at sunspot-minimum

taneous sunspot-numbers for the same months and years. The continuous lines show the normal percentages of precipitation and the dotted lines show the sunspot-numbers from Table 4, direct in the first two groups and inverted in the other two.

The States used in computing the average were: Idaho, Nevada, Utah, Colorado, Arizona, and New Mexico for the Rocky Mountain group; North Dakota, South Dakota, Minnesota, Iowa, Missouri, and Arkansas for the Central States; North Carolina, South Carolina, Georgia, Alabama, and Florida for the South Atlantic States; and New England, New Jersey, Maryland, and Virginia for the North Atlantic States.

The differences in the percentage of precipitation between the year of sunspot-maximum and the year of sunspot-minimum were determined for each State and plotted in the center of the State and lines of equal difference were drawn as in Figure 2. This chart shows that the difference equaled or exceeded 20 per cent in the States from Arizona northward to Idaho and Washington, and that there was an inverse difference of 20 per cent or more in the Atlantic Coast and East Gulf States. In New Mexico, Arizona, and California the excess was greater than 30 per cent while the inversion exceeded 30 per cent in Florida and New England. Such differences, while not representing the total variations, are worthy of consideration.

It is interesting to note that the greatest excess of rainfall at sunspot-maximum occurs in the Central Continental Area, where the lowest pressure is found in spring and summer, and the reverse condition is found near the Atlantic Coast where the highest pressure is found, indicating that these conditions are intensified at sunspot-maximum.

Canton, Massachusetts

AMERICAN GEOPHYSICAL UNION

TWENTY-THIRD ANNUAL MEETING

SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY

REPORTS AND PAPERS

Washington, D. C.
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EARTH'S MAGNETIC FIELD AND ACTUAL HEIGHTS IN THE IONOSPHERE

H. W. Wells

(Abstract)

When a radio wave is propagated into the ionosphere it becomes divided into separate wave-components under the influence of the Earth's magnetic field. This is fundamentally a Zeeman effect wherein an electromagnetic wave is propagated in an ionized medium in the presence of a magnetic field. The separation in frequency between the individual wave-components provides a measure of the intensity of the Earth's magnetic field at the actual height in the ionosphere from which the signals are being returned.

At Huancayo (Peru) separate records were maintained of critical frequencies of both ordinary and extraordinary wave-components. Mean hourly values of the frequency-separation as observed over a period of four months were used to obtain mean hourly values of magnetic field-intensity H in the ionosphere at the height of maximum electron-density. A plot of these values reveals a form of diurnal variation for H. Since H is measured at the height of maximum electron-density it must be assumed that the diurnal variation in H, as observed by this technique, is a result of the change in actual height of the region of maximum electron-density of the ionosphere.

If we assume the Earth to represent a uniformly magnetized sphere, the variation of H with height above the Earth is readily calculated. This provides means for conversion of the intensities of H as observed from the ionospheric measurements into terms of actual heights.

It is shown that the form of diurnal curve obtained in this manner is similar to the diurnal curve of ionospheric heights obtained independently by other means.

The technique outlined is particularly applicable at the magnetic equator. With especially developed apparatus probably a single observation could be used to obtain accurate measurement of the intensity of the Earth's magnetic field in the ionosphere.

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GEOMAGNETIC SURVEY OF A PORTION OF SOUTHEASTERN NEW YORK

Richard A. Geyer

(Abstract)

The area covered by this survey of approximately 130 square miles involves portions of northern Westchester, Putnam, and southern Dutchess counties. Four hundred and eighty-six stations were occupied at which the vertical component of the Earth's magnetic field was measured with an Askania magnetometer. These data, after the usual necessary corrections were made, were plotted on a map on a scale of 1:30,000. The resulting isogam chart was superimposed upon a geologic map of the area in an attempt to correlate changes in the magnetic field with changes in the geologic characteristics found here.

A rather close correlation was shown to prevail in most instances. In a few cases where the correlation was not too well defined a detailed study of the mineralogic and petrographic characteristics of the rocks involved was begun, including thin-section studies and measurements of their magnetic properties. However, final results of this aspect of the work cannot be given at present, since the completion of this phase of the study has been interrupted by the exigencies of the present crisis.

The area surveyed included formations ranging in character from only slightly metamorphosed sedimentary to highly metamorphosed igneous and sedimentary rocks. The total variation in the Earth's field in this area was approximately 4,000 gammas. Several well-defined anomalies rang-

ing in value between 2000 and 2500 gammas (1 gamma = 0.00001 cgs unit) are present in one zone of schists and pelites. They are extremely elongated, have an approximately north-south orientation, and a length varying from one to three miles.

It would appear from an analysis of the information available at present that these anomalies are caused primarily by an intrusion of a sheet-like mass of igneous origin whose susceptibility is much higher than that of the country rock.

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GEOMAGNETIC BAYS, THEIR FREQUENCY AND CURRENT-SYSTEMS

H. B. Silsbee and E. H. Vestine

(Abstract)

In extension of the previous work on bays by BIRKELAND, STEINER, WIECHERT, McNISH, CHAPMAN and BARTELS, and HATAKEYAMA a study was made of the frequency and current-systems of geomagnetic bays. The field of bays at ground-level is highly complicated and variable, especially in the auroral regions, and hence ill-adapted for study using data measured at only a small number of points on the Earth. The present study was based, therefore, on a selection from somewhat more complete data of the Polar Year 1932-33 than was available to earlier writers.

The daily and annual variations of frequency in bays were examined for four different zones of latitude. These included (I) stations near the center of the auroral zone, (II) the auroral zone, (III) middle latitudes, and (IV) the equator. The characteristics of bays, though in some respects rather similar in each of the four Groups, differ notably in other particulars from Group to Group. For statistical purposes selection-rules were devised so that a single year of observations gave approximately the same number of bays at each station; these rules were purposely biased in favor of the simpler and more isolated examples of the phenomenon.

For all Groups the monthly percentage of total of bays per year shows a double-wave component with maxima near the equinoxes and minima at the solstices.

The daily variation of frequency of bays was also examined for positive and negative bays separately. Near the center of the auroral zone the frequency varies little with hour of day. At all stations of Groups II to IV there is a marked dependence of both positive and negative bays in frequency upon local geomagnetic time. Along the auroral zone the negative bays outnumber the positive bays in the proportion about nine to one. The negative bays appear with maximum frequency at about 1^h local geomagnetic time, whereas positive bays appear most frequently at about 18^h. In low and middle latitudes positive bays were found to outnumber the negative bays in the approximate proportion three to two. A marked maximum appears for positive bays near local geomagnetic midnight whereas negative bays are more frequent at 16^h. The world-wide character of bays appears to be that, in general, positive bays in low and middle latitudes correspond to either negative or positive bays (or both) along the auroral zone.

An electric current-system of bays was derived from data based on the averages of many bays in each zone. The average magnitude of the total disturbance of these selected bays was about 150γ near the center of the auroral zone, 450γ near the auroral zone, 40γ in middle latitudes, and 30γ in equatorial regions (1γ = 0.00001 cgs unit). Estimates of heights and intensities of electric currents flowing along the auroral zone were estimated for two simple assumed forms of current-distribution. The heights obtained agree well with previous less detailed results of BIRKELAND, GOLDIE, CHAPMAN and VESTINE, and McNISH, and place the probable location of currents in the region near 100 km and less than 200 km above the Earth. An approximation to the average current-system of bays was next deduced assuming the currents confined to a spherical shell concentric with the Earth at a height of 150 km, using average vector-changes of many bays taken for time of maximum. This current-system differs from the electric current-system of storms proposed by CHAPMAN since there appears little evidence of a storm-time part; the current-system resembles that for the diurnally varying component S_D of storms though notably distorted in form in polar regions. The westward current flowing along the auroral zone shows an intensity relatively much greater than the eastward current. Current-systems for individual bays show the same general characteristics but evince marked seasonal changes in the polar parts of

the current-system.

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THE ANNUAL VARIATION OF GEOMAGNETISM

E. H. Vestine

(Abstract)

During magnetic disturbances the horizontal-intensity (H) component of the geomagnetic field is depressed below normal and to a degree depending on the intensity of disturbance. Following the depression in the field a recovery towards a higher value of H appears. This recovery is in general not complete before the onset of the effects of new disturbances. Since disturbances vary both in number and intensity with time of year, they contribute the major part of an apparent annual variation.

The annual variation as shown by monthly mean departures from the annual means of the geomagnetic elements is relatively small in amplitude. Throughout low and middle latitudes it is most marked in the geomagnetic north component for which it has an amplitude of the order about ten gammas ($1\gamma = 0.00001$ cgs unit). Because of the small amplitude and long duration of the variation it is difficult to derive accurately at most observatories. During recent years the improved techniques in the operation of geomagnetic observatories permit in many cases a satisfactory derivation without recourse to averaging the results for several years.

The annual variation was derived using data for about 65 observatories of the Polar Year, 1932-33. The results proved satisfactory for the geomagnetic north and east components but were highly erratic in the vertical component except in high latitudes. A similar derivation was made for a period of 24 years for ten stations in low and middle latitudes; the results for the vertical component were again found to be somewhat erratic. The geomagnetic north component was small near the geomagnetic poles and increases rapidly equatorwards to a maximum at the auroral zone. Just outside the auroral zone this component diminishes rapidly with decreasing latitude, attaining a secondary maximum near the equator. The geomagnetic east component was found to be small in all latitudes. The vertical component is largest near the center of the auroral zone and zero near the equator where a reversal in sign occurs.

The annual variation can be separated into two parts. One part is symmetrical about the equator with a minimum near the equinoxes and varies with latitude proportionately to the annual average of disturbance in amplitude. CYNK showed that the remaining part is nearly sinusoidal in character with a period one year, with minimum at the winter solstice and maximum at the summer solstice. The annual variation thus comprises both an annual and a seasonal component.

The annual variation varies in amplitude with sunspot-cycle, the amplitude for years of sunspot-maximum being about twice that for years of sunspot-minimum.

A possible electric current-system of the part symmetrical about the equator closely resembles that corresponding to the annual average of the daily means of disturbance, if the lines of current-flow are assumed to flow in closed circuits in a thin layer in the Earth's atmosphere at constant height. Lines of current flow from east to west in all latitudes with maximum concentration of current in polar regions. In the case of the sinusoidal part the current-lines are roughly along parallels of geomagnetic latitude opposite in direction in the Northern and Southern hemispheres, and increasing in intensity from zero near the equator to a maximum in polar regions, where the variation with time of year is marked. This notable seasonal variation also gives rise to considerable distortion in the average current-system of geomagnetic disturbance.

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RECENT ALTERATIONS IN GEOMAGNETIC SECULAR VARIATION IN EASTERN NORTH AMERICA

H. Herbert Howe

As is well known, there was about 1933 a large, sudden alteration in the rate of change of magnetic declination (D) in the eastern part of the United States [see 1, p. 7, of "References" at end of paper]. In 1941, the author noted [2] that in recent years the rate of change of horizontal intensity (H) had altered almost as suddenly and by a considerably greater amount.

Figure 1 shows the annual means of the declination and horizontal intensity at the Cheltenham Magnetic Observatory since 1902, and Figure 2 shows on a larger scale the annual and monthly means beginning with 1928. On both graphs, the means through 1932 are based on ten selected quiet days of each month, and are final values, while the values since 1932 are based on all days, and are preliminary values.

When the rate of secular change is variable, the determination of the rate applicable to any particular month is difficult because of the annual variation. The principal feature of this phenomenon at Cheltenham is the increase of horizontal intensity and the decrease of west declination in the summer. Thus, in Figure 2, the circle showing the annual mean is in nearly every case below the circles for the summer months. However, Figures 1 and 2 show definitely that there was a rapid change in the rate of secular change of D in 1933 and 1934; and that the rate of secular change of H has decreased rapidly during the past few years, being now about zero.

In comparing the rate of change of D with that of H, it may be noted that a change of 1′ in D corresponds to a field of between five and six gammas (1γ = 0.00001 cgs unit) normal to the Earth's field. This suggests the desirability of a single graphical representation of the combined change of D and H. One method would be to plot D against H, one point for each annual mean. For more accurate representation, we might plot the north component against the west component. On such a graph, varying secular change would appear as varying distance or direction between consecutive points.

However, varying distance and direction can be shown more effectively by plotting only the vector-difference between consecutive points, drawn from a common origin. Each vector of such a graph represents the horizontal projection of the field to be added to the mean field for one year to obtain the mean field for the next year. Figure 3 shows such a graph, only the termini and the common origin of the vectors being drawn. For convenient reference, consecutive points are connected by lines.

An example of the interpretation of Figure 3 is as follows: The point marked 14 indicates that the horizontal vector-difference between the mean field for 1913 and the mean for 1914 represented a change of 20γ to the westward and 92γ to the southward. That is, the west component increased 20γ and the north component decreased 92γ.

Most of the points are grouped within a small region, since the progression was nearly uniform for the periods concerned. There have been two excursions from this region, the present one being, to date, of about the same magnitude as was the excursion of 1912-17. The eastward travel from 1933 to 1935 represents roughly the alteration in rate of change of D, while the northward motion since 1935 represents roughly the alteration in rate of change of H.

The phenomena described above appear to be general throughout much of eastern North America. To illustrate this, Figure 3 includes similar data for the San Juan Magnetic Observatory and for its predecessor at Vieques. The values through 1930 are final, and are based on ten quiet days of each month; the later values are preliminary, and based on all days.

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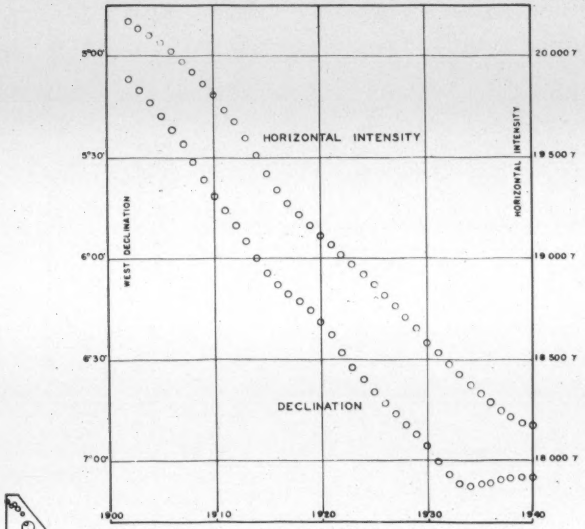

Fig. 1--Annual mean values of declination and horizontal intensity, Cheltenham Magnetic Observatory (lat. 38° 44′ N, long. 76° 50′ W)

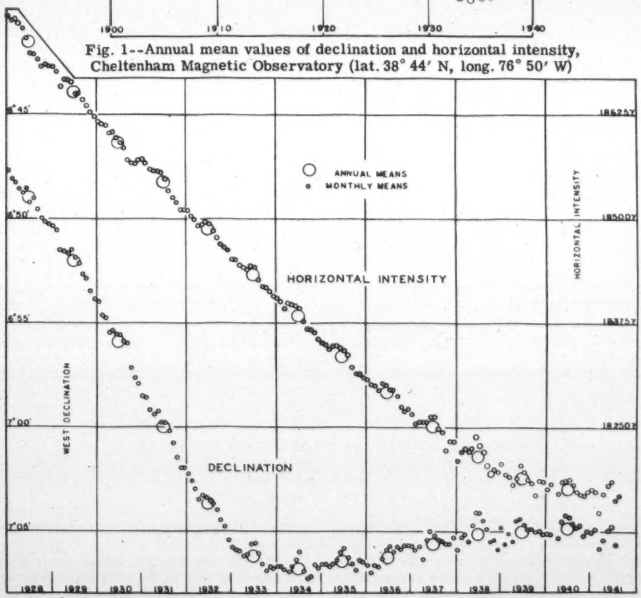

Fig. 2--Monthly and annual means, Cheltenham Magnetic Observatory, 1928-41

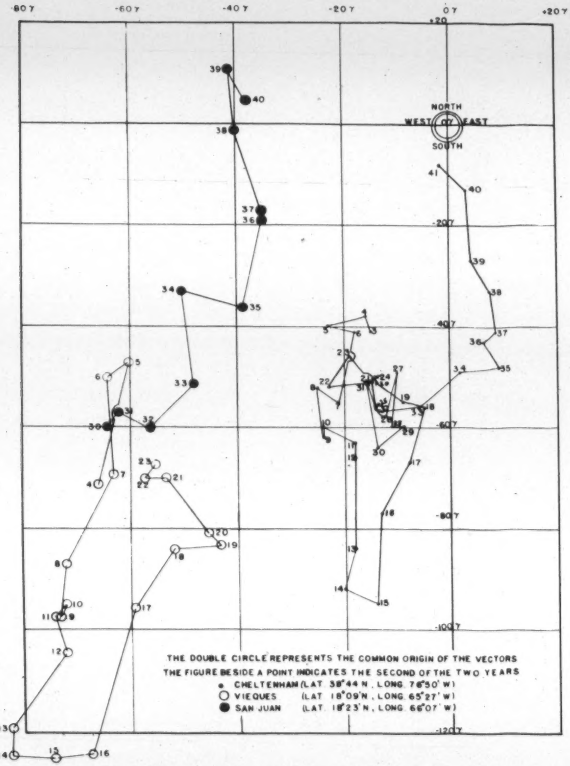

Fig. 3--Horizontal projection of termini of vector-differences of mean fields for consecutive years

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METHODS USED IN THE PRODUCTION OF THE 1940 ISOGONIC CHART OF THE UNITED STATES

David G. Knapp

The outstanding feature with which magnetic cartography must concern itself is the widespread prevalence of local irregularity in the distribution of the magnetic field. In order to give magnetic charts some practical utility and bring out more clearly the systematic changes, it is necessary to suppress much of the irregularity; but a result of this is that users of the charts are apt to be denied an appreciation of the severity of local disturbance and its well-nigh universal occurrence. Especially is this pertinent with respect to magnetic declination. The intensity-

elements have sweeping systematic gradations arising from the basic geometry of magnetic fields, whereas the orientation of the field is characterized by theoretical homogeneity so far as its main constituent is concerned (that is, the dipole field). For the intensity-elements, the systematic changes usually predominate over the regional effects; but for magnetic declination the systematic changes are often subordinate and can only be brought out by rather stringent smoothing of the observed anomalies.

Even though it were attempted to depict all the irregularity that the observations indicate, some smoothing would be necessary, since the observations are, in general, far too sparsely scattered to develop fully all the features of the magnetic "landscape". Consider, for example, single anomalous values; any such value would be unlikely to be representative of an appreciable area. That is, the immediate and most likely interpretation of a single high value would be that the station at which it was observed happened to be situated near the crest of a minor focus of high values, having no significance except in its immediate vicinity; and any attempt to make a chart conform accurately with such a value would unduly expand its influence over the region intervening between the station at which it was observed and those surrounding it. But the same principle applies to any disparity, large or small, between a particular value and its neighbors. Consequently, we must adopt a rule that there shall be at least enough smoothing so that each anomaly depicted on the chart is well supported by several different stations distributed over its area.

The amount of smoothing suitable for a given chart depends upon the use for which the chart is intended; thus, the world charts issued by the hydrographic offices of the various governments are quite highly smoothed, and properly so in view of their function of indicating mean values at sea; but even such charts do not go so far as to show only the dipole field. Isogonic charts of continental and smaller areas usually require appreciably less smoothing, since it is desirable to make the sinuosities of the lines give an indication of the amount of irregularity in different regions.

Enough has been said to show that the smoothing problem is what lends individuality to magnetic cartography and blocks complete fulfillment of one of the recognized desiderata of such work--the production of a continuing series of charts of a given area having mutually consistent representations of the distribution. In the production of the isogonic chart of the United States for 1940 (one of a series issued at five-year intervals) it was decided to work from the previous chart as a basis. Borrowing a leaf from a practice followed in magnetic prospecting, the systematic changes were removed so as to result in an isanomalic chart. The datum used was a highly smoothed isogonic chart prepared for the purpose. The isanomalic chart was drawn to an interval of 5′ for small anomalies and one of 20′ for those outside the limits ±20′. The resulting chart represents the difference between the distribution shown by the isogonic chart for 1935 (with a number of minor revisions) and that shown by the datum-chart. Although scattered observations at new stations were available in some regions, they were not generally utilized because time did not permit the study that would have been required to integrate the new work with the old while maintaining the previous standard of smoothness.

Where irregularity was pronounced there was some uncertainty as to the proper delineation of anomaly in the interstices between the isogonic lines for 1935, and for this reason some of such areas were developed more fully by making use of the observed anomalies at stations (again referred to the same datum-chart). In all such instances, however, the endeavor was to hold the isanomalic lines in consonance with the isogonic lines for 1935, using the station-data merely to fill in the gaps.

The next step was the revision of the datum-chart for secular change for the period 1935-40. This entailed the (indirect) use of every available repeat-observation and of data from magnetic observatories. The data from repeat-observations had initially been reduced to mean of month by established procedures; and as a result of a study by Dr. H. H. HOWE there was available an isoporic chart which was used to shift the pattern of the datum-chart so as to allow for the five-year change.

After shifting the datum-lines, they were recombined with the isanomalic lines to produce the chart for 1940. It would have been desirable to make the new chart so closely similar to the old one that interpolated values would differ only by the amount of the secular change. This was not possible, because of the altered relation between the anomaly-pattern and the datum-lines, resulting from the shifting of the latter to allow for secular change. The new chart, however, does depict as nearly the former distribution as possible, except for the minor revisions already mentioned.

It is believed that by extending the technique somewhat further there would result a general method of magnetic cartography that would represent a substantial advance over conventional techniques. The smoothing problem is greatly simplified by the removal of the systematic changes represented by the datum-chart, and furthermore the resulting anomaly-chart can readily be drawn to a sufficiently close interval to bring out all the irregularity legitimately deducible from the observations. The general procedure would be similar to that used in the present instance except that the isanomalic lines would be based wholly and directly on new treatment of the observed anomaly rather than on former smoothing attempts. Having once established the isanomalic pattern, it could be combined with a new version of the datum-chart whenever a new chart was desired, without the necessity of resmoothing the observations, since all the smoothing would be done once for all when the anomalies at the stations were considered in the drawing of the isanomalic lines. The advantage of this method is particularly evident where the systematic part of the distribution shows steep gradations making it difficult if not impossible in the ordinary procedure to maintain consistent criteria of smoothing in different directions and under varying kinds of anomaly-patterns.

A more extensive explanation of the method proposed for future use and the shorter one used for preparing the latest isogonic chart has been published, together with a copy of the chart in question, in the Journal of Terrestrial Magnetism and Atmospheric Electricity [v. 47, pp. 53-62, 1942].

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ATMOSPHERIC-ELECTRIC OBSERVATIONS AT THE NEEDHAM LABORATORY FOR COSMIC TERRESTRIAL RESEARCH

Harlan T. Stetson

In addition to the continuous measurement of field-intensities in the broadcast and high-frequency bands three instruments are regularly in use at the Laboratory for Cosmic Terrestrial Research at Needham, Massachusetts, for measuring atmospheric-electric phenomena (Fig. 1): (1) A potential-gradient apparatus; (2) an ion-counter for determining the number of small negative ions of a given mobility; (3) a point-discharge apparatus for determining atmospheric-electric discharges between the Earth and the sky in either direction. The first of these at present is manually read, whereas the other two are automatically recording.

Potential-gradient apparatus--The potential-gradient apparatus consists of a horizontal rod maintained at a distance of two meters above the ground at the outer extremity of which is an ionium-collector loaned by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. The collector is to insure that the potential of the rod is maintained at the potential of the atmosphere at the point of contact. The other end of the rod extends through an aperture in the wall of the Laboratory and passes through a fused-sulphur plug to the insulated terminal of a Wulf bifilar electrometer. The case of the electrometer is connected to the ground. Readings are taken at hourly intervals throughout the day and occasionally throughout the night. In the electrometer the separation of the two threads is read against a transparent scale. The reading is an index of the atmospheric potential-gradient existing between the Earth and the outboard end of the rod (Fig. 2). The electrometer has been calibrated by means of imposing fixed voltages from radio B-batteries from which calibration of the instrument in volts has been derived. There is, of course, a warping of the electric field of the Earth due to the building in the neighborhood of the rod. Correction for this is to be made from the determination of the electric potential between a horizontal wire, stretched in an open field adjacent to the Laboratory, and the Earth. For the purpose of relative changes in the potential-gradient, however, a direct reading of the electrometer attached to the horizontal rod is sufficient.

The average diurnal variation of the potential-gradient at Needham determined from several months' observations is shown in the accompanying curve (Fig. 3). Seasonal and secular trends will be determined with the increasing length of the series of observations.

Ion-counter--The ion-counter is a modified form of the Ebert ion-counter adapted from specifications utilized in the general design of the ion-counters employed by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, with one important modification. This modification is to substitute for the usual electrometer a General Electric pliotron tube known as FP-54 (Fig. 4). This, through appropriate circuits, leads to a Brown recording-potentiometer

Fig. 1--Cosmic Terrestrial Research Laboratory, Needham, Massachusetts

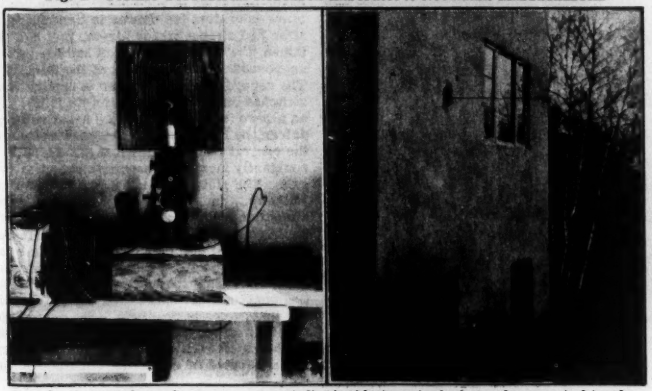

Fig. 2--Potential-gradient apparatus (left--inside terminal of a rod connected to electrometer; right--external projecting rod and collector)

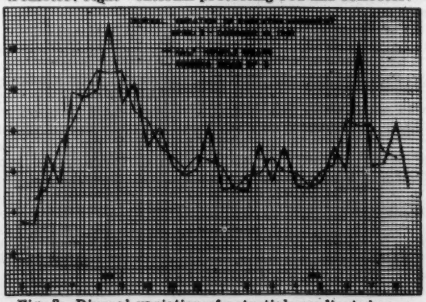

Fig. 3--Diurnal variation of potential-gradient; hours expressed in Eastern Standard Time

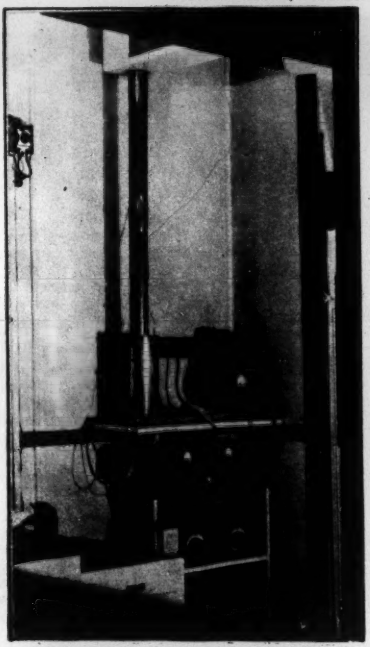

Fig. 4--Pliotron ion-counter as installed at Needham Laboratory

used as a recorder of the plate-current of the tube. At present the potential imposed upon the inner of the two co-axial cylinders is -22 volts. The air-flow, maintained by an induction-motor blower, is found to be reasonably constant with an exchange of air of 93 liters per minute. The central rod, which remains unchanged except for the collection of negative ions, is connected directly to the grid of the FP-54 tube. In addition to the insulation of the rod from the glass tube, insulation has been improved and it is believed rendered satisfactory through the coating of the outer portion of the tube with ceresine wax. Calcium-chloride driers are maintained in the chamber with the tube.

A control-box containing a telechron clock-movement operates a series of cams for making the appropriate contacts in the cycle of operation in the beginning of each hour. At the beginning of the operation the blower is first put into operation and after a steady air-current has been attained, the central rod which has been grounded, ungrounds and the filament of the tube lights. The recording galvanometer is automatically switched on and the pen takes its initial position as a zero for the record. As negative ions are driven, by the charge on the inner cylinder, to the central rod and collect there, there is a constantly increasing negative potential on the grid. The plate is maintained at a potential of +6 volts. Since the plate-current of the tube is a function of the difference of potential between the filament and the grid, the change in the plate-current in a given interval of time is a direct function of the number of negative ions collected during the same interval. The operation continues for approximately 3-1/2 minutes, and the change in readings of the pen on the recorder-sheet then becomes the index for the number of negative ions collected in the interval. The calibration of the instrument has thus far been effected by observing simultaneous readings with a manually operated Ebert counter.

Since there may inevitably exist some leak in the insulation and also since intermediate ions of lower mobility may be collected along with the small negative ions of approximately equal mobility, a duplicate tube of the same dimensions as the counter-tube is placed directly above the counter-tube with an independent insulated co-axial rod. This arrangement is known as the filter and is constructed in accordance with the specifications used by WAIT at the Carnegie Institution. If a negative potential is placed upon the inner cylinder of this filter equal to that imposed upon the counter-tube during its operation, then the filter should extract from the air-flow before it reaches the counter all of the small ions which the counter would normally collect. Stray ions which pass under these circumstances may still be collected by the rod of the counter-tube itself and any leakage incident to the FP-54 tube will be recorded. The control-box, therefore, after an interval of 3-1/2 minutes automatically applies -22 volts to the inner co-axial cylinder of the filter and for the next 3-1/2 minutes the pen of the recorder will indicate the number of stray ions still collectable on the rod of the counter-tube in spite of the presence of the filter plus any change in plate-current due to insulation-leakage during a run of 3-1/2 minutes. This, then, provides the correction to the count registered by the counter-tube itself. The correction is then applied to obtain the final readings. A complete schedule of operation at the beginning of each hour is shown on the diagram illustrating an upright section of the apparatus (Fig. 5). A sample of the recordings obtained is shown in Figure 6.

The apparatus may still be considered as being in the experimental stage. The deflections obtained on the recording galvanometer can be appreciably increased if desired through the addition

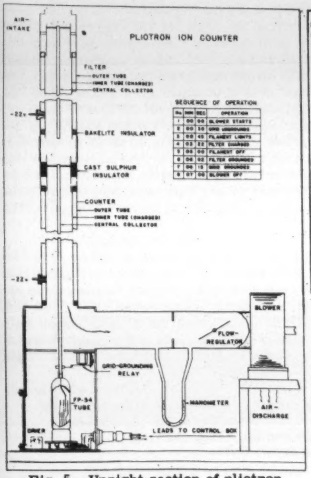

Fig. 5--Upright section of pliotron ion-counter

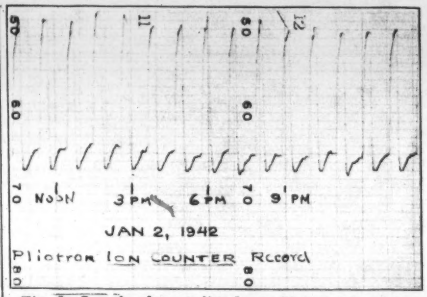

Fig. 6--Sample of recording from pliotron ion-counter

of a one-stage amplifier between the ion-counter FP-54 tube and the recording galvanometer.

It should be stated in this connection that according to the manufacturer the characteristics of the FP-54 tube are such as to make possible detections of current of 10^{-14} ampere. Figure 7 is a wiring diagram of the electrical connections.

Point-discharge apparatus--The point-discharge apparatus consists essentially of a Cambridge Instrument Company thread-recorder, the galvanometer of which has a full-scale deflection in either direction of 2-1/2 microamperes and an internal resistance of 2,100 ohms. As installed, a ground-wire leading from the water-main of the building is connected to one terminal of the galvanometer conventionally adopted as positive. A second wire leads from the other terminal of the galvanometer to a vertically pointed rod supported on a glass insulator from a cross-arm at the top of a 60-foot wooden pole on the Laboratory grounds. With any passage of an electric discharge from the sky to Earth by way of this pointed rod, or from the Earth to the sky, the thread-recorder will indicate the amount of

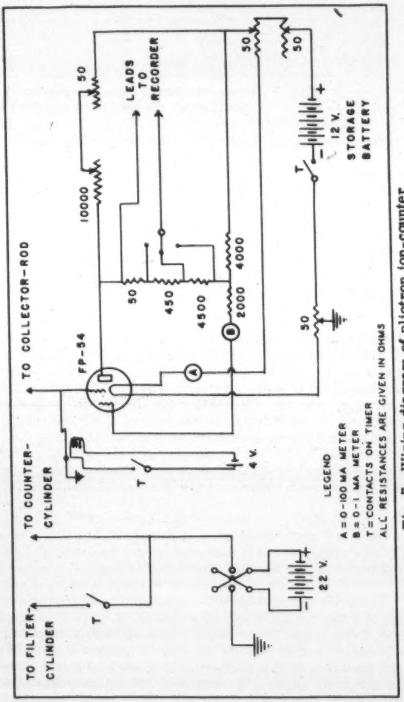

Fig. 7--Wiring diagram of pliotron ion-counter

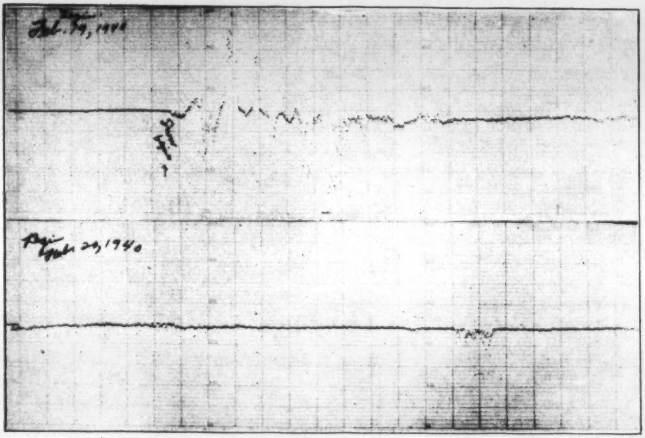

Fig. 8--Point-discharge records February 19 and 20, 1940, showing oscillatory discharge accompanying snow-storm

current passing provided the current passed is in excess of the threshold-value of the galvanometer. The connection of the galvanometer is such that a current passing from Earth to sky moves the needle to the right of the central point, whereas a current passing from sky to Earth moves the needle to the left of the central point. The position of the needle is recorded at one-minute intervals upon a drum bearing the recorder-paper which rotates at a rate of one revolution per day. The record sheets are changed daily at 09^h Eastern standard time (75° west meridian mean time). In ordinarily fair weather the recording-needle yields a straight-line trace at its middle position since the fair-weather current is of an intensity of the order of but 2×10^{-16} ampere per cm^2. At irregular intervals a discharge may occur for which no obvious cause is apparent. Such a discharge, so far as has been observed, may happen at any hour of the day and last for an hour or so.

Other definite discharges are traceable to changes in meteorological conditions. The onset of a sudden shower is almost invariably preceded by a discharge of 0.50 microampere or more in the direction of sky to Earth. This may last for an interval of minutes or several hours. In many instances this period is followed by a discharge in the opposite direction from Earth to sky for an equal interval, after which the needle will regain its normal position, or there may be a persistence of oscillation. In the case of a thunder-storm there will be recorded violent oscillations of the needle in both directions often exceeding the limits of the scale. In this connection it should be remarked that storms accompanied by relatively long rains may or may not show anything other than the normal record. A northeast storm on May 21, 1940, for example, gave a perfectly normal fair-weather curve of no measurable deflection.

A snow-storm is almost invariably accompanied by periods of oscillating discharges of an hour or more each, first in the direction of sky to Earth and second, Earth to sky (Fig. 8). An exception to this, however, occurred on the morning of February 28, 1940, when no measurable deflection was shown although snow was falling.

The most remarkable recording obtained since the installation of the apparatus in February, 1940, was the record obtained on March 9, 1942. During the passing of a low with heavy precipitation, a discharge in the sky-to-Earth direction began at 09^h, varying in intensity from 0.3 to 1.5 microamperes until shortly after noon. At about $12^h\ 20^m$ the needle suddenly passed off the scale in the direction of sky-to-Earth and remained so for nearly four hours. At $13^h\ 00^m$ a Triplett microammeter capable of recording 200 microamperes was connected in series with the galvanometer of the thread-recorder and it was found that a current of 50 microamperes was recorded. This remained practically steady for nearly two hours. It should be stated that heavy rain had

been falling throughout the morning and that the rain suddenly stopped at about the time of the heavy discharge. At $14^h\ 45^m$ the meter was fluctuating between 50 and 55 microamperes while low scudding clouds were passing from the south-southwest. There was no evidence whatever of thunder-storms. At $15^h\ 55^m$ the needle returned to within 0.2 microampere of its zero-position and remained so for about one hour. The sky had then mostly cleared and the Sun was out. At $16^h\ 50^m$, with the appearance of low scudding clouds overhead, a reverse discharge appeared in the direction of Earth-to-sky, fluctuating in intensity between 15 and 20 microamperes. At $16^h\ 53^m$ the discharge again reversed registering 35 to 40 microamperes sky-to-Earth. The current mounted to 45 to 60 microamperes at the approach of high wind and a sudden shower. One minute later, another reversal came with registrations attaining 17 to 25 microamperes at $17^h\ 00^m$. The current remained steady in this direction, Earth-to-sky, until $17^h\ 30^m$. After this there was a slow steady decrease with minor fluctuations until 16 microamperes was recorded at $22^h\ 00^m$, EST, the last reading of the day.

The automatic recorder showed that the needle remained off scale on the record sheet until $03^h\ 00^m$ on the morning of March 10. By that time the reading showed fluctuations of about 0.1 microampere either side of the zero for the next five hours. The sudden return of the needle to its near normal position coincided very nearly with a snow-squall reported as occurring at about $03^h\ 00^m$. The needle then remained undisturbed until the rain-storm of March 11. It is thought that the detailed description of the performance of this apparatus on March 9 is of special interest since nothing of the kind has been observed before or since within the 25-month period of recording.

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ON THE ANOMALOUS DIURNAL VARIATION OF AIR-CONDUCTIVITY AND POTENTIAL-GRADIENT AT THE HUANCAYO MAGNETIC OBSERVATORY

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(Presented by O. H. Gish)

Some anomalous features of atmospheric electricity at the Huancayo Magnetic Observatory and a tentative explanation of them have been briefly described by GISH [see 1 of "References" at end of paper], who also outlined, in a memorandum dated January 27, 1941, the reasons for the present investigation as follows:

"It is desirable that tests be made of the proposed explanation of the following extraordinary aspects of atmospheric electricity at the Huancayo Magnetic Observatory:

"(a) The type of diurnal variation in potential-gradient and air-conductivity, which is especially remarkable for the large and abrupt change in the magnitude of those elements during an hour centering, roughly, at 07^h and which is especially common in the dry season.

"(b) The small average value of the air-earth current which is certainly less than one-half what one would expect at a station whose altitude is 3.3 km above sea-level.

"(c) The relatively small value of the ratio of positive to negative conductivity which is often less than unity at night.

"One clue to the proposed explanation was provided by the remarkably large concentrations of nuclei observed there at 08^h [2]. These nuclei presumably come from a distant source . . . . and, therefore, must be carried by the more general air-circulation and introduced into the air near the surface by turbulent stirring (eddy-diffusion). However, when the lower air becomes stable, turbulent mixing with the higher stratum is no longer effective and hence the rate at which nuclei are introduced to the surface-air is reduced. At such times the concentration of nuclei in the surface-air gradually diminishes and the conductivity increases at a rate which depends, perhaps, on the rate at which the nuclei coalesce and settle to Earth or on the rate at which they are dispersed by other processes. In the morning after sunrise when the air in the lowermost stratum becomes heated the stability of that stratum decreases and finally turbulent mixing of this with the higher stratum sets in, thus bringing more nuclei into the surface-air and of course decreasing the conductivity of the air there. The latter occurs rather abruptly and a decrease of nearly 80 per cent of the value at 06^h is usually effected in the interval $06^h\ 30^m$ to $07^h\ 30^m$ on most quiet days in the dry season.

"The surprisingly low value of the air-earth current is accounted for if it is assumed that nuclei are usually abundant in the general circulation over the vicinity of the Observatory, not only in daytime but also at night when, near the surface, the concentration of nuclei is, presumably,

relatively small and the air-conductivity large. It is of course necessary that the vertical extent of this nuclei-bearing stratum be adequate--probably not less than one km nor more than three km, depending upon the concentration of nuclei in it and upon how the latter varies with height--to account for at least a twofold increase in the value of the resistance of a vertical column of the atmosphere and the consequent deficit in the air-earth current-density at Huancayo.

"This picture also contains in it the elements needed to explain the small values of the ratio of positive to negative conductivity derived from registrations, particularly those for the night. Thus if the conductivity near the surface decreases with altitude on account of an increase of nuclei-concentration with altitude then, when the potential-gradient is positive, there is a tendency to build up a negative space-charge in that region. This counteracts, to some extent, the so-called 'electrode-effect' in which a positive space-charge is developed in the air near the Earth. It then follows that the ratio of positive to negative conductivity of air near the Earth's surface is reduced.

"Another factor which may contribute to the increased conductivity near the surface at night is radioactive matter which may be expected to occur in greater concentration there when a shallow stable stratum of air has developed adjacent to the Earth.

"From an inspection of the meteorological records it appeared that the abnormal diurnal variation in conductivity and potential-gradient is clearly correlated with the type of diurnal variation of temperature in the open air and also with the steadiness of the wind, and may depend somewhat upon wind-direction and velocity, but no other significant correlation between these electrical features and meteorological phenomena was noted. These observations provide support for the view that the diurnal variation of conductivity and potential-gradient at Huancayo on most quiet days is associated with the development of a shallow stratum of air adjacent to the Earth during the night--the latter in turn implies little or no mixing with the higher overrunning air. This stratum is regarded as shallow because the air-earth current is apparently unaffected by it. It can scarcely extend higher than 0.1 km.

"It is desirable to obtain further tests of this theory because if it is finally verified then a large part of the diurnal variation of conductivity and potential-gradient at Huancayo must be attributed to some meteorological circumstances whose importance for this phase of atmospheric electricity has thus far not been generally recognized. One rather obvious test would be provided by measurements of the concentration of nuclei made early in the morning, say before 06^h, when according to the theory nuclei are considerably less abundant than in daytime, especially during the dry season. It is expected that the results of this test will have interest for meteorologists quite apart from its bearing on the explanation of the electrical phenomena."

The observations were made between August 7 and 27, 1941, during the height of the dry season. Observations were not made on a few days in this period on account of unusually cloudy weather. In addition to the regular nuclei-observations at 08^h, observations were made at about 06^h and 07^h, thus covering the period during which the abrupt changes in conductivity and potential-gradient usually occur. The total number of days on which observations were made was 15 but on one of these the observation at 06^h was missed.

Each count of nuclei, listed in the third column of Table 1, is the mean of ten counts (that is, ten different samples). Other atmospheric-electric and meteorological elements which apply to the same period as the nuclei-counts are also listed in Table 1; these include positive conductivity, negative conductivity, potential-gradient, barometric pressure, relative humidity, temperature, and wind-direction and force. Wind-force was estimated on the Beaufort scale because the anemometer was not recording this element correctly. The times of sunrise given in the footnote to Table 1 were computed from the American Ephemeris and Nautical Almanac for 1941 but are not corrected for altitude.

It is evident from a glance at Table 1 that the concentration of nuclei is usually considerably less at 06^h than at 08^h; in fact, there is only one exception, namely, in the data for August 16. There is a progressive increase from 06^h through 07^h to 08^h in nine cases out of fourteen and the count at 08^h is greater than that at 07^h in thirteen cases out of fifteen. In general this trend is in qualitative agreement with the decrease in conductivity and the increase in potential-gradient. There appears to be no simple dependence of the change in nuclei-concentration any of the meteorological factors listed in Table 1. On August 16, when the nuclei-count was very low for this Station, and there was no appreciable change from 06^h to 08^h, the relative humidity was unusually high, and the temperature at 06^h was higher than on any other day for which measurements were made. However, on August 24, which ranks next to August 16 in respect to smallness of count and smallness in the change of the count, the relative humidity was somewhat below average and the temperature at 06^h was less than that on August 21 when the greatest average count and the greatest change were observed. Apparently there is involved here some meteorological circumstance which is not readily identified by meteorological observations at a single station at the Earth's surface.

Table 1--Nuclei-counts and atmospheric-electric and meteorological elements, Huancayo Magnetic Observatory, August 7-27, 1941

Date	75° west mean time	Nuclei-count, N	Conductivity λ_+	Conductivity λ_-	Potential gradient	Air-earth current-density	Barometric pressure	Relative humidity	Temperature	Wind Direction	Wind Force
	h m	10^3/cc	10^{-6} ESU		V/m	10^{-7} ESU	mm	pct	°C		
1941											
Aug. 7	06 10	2.2	591	692	(21)	9.0	517.9	71	-0.5	NNW	2.0
	07 25	29.6	154	162	(58)	6.6	518.3	61	5.3	N	2.0
	08 10	46.3	120	119	(91)	7.2	518.7	53	7.7	WNW	2.0
8	06 12	5.0	700	481	16	6.3	517.1	61	0.0	W	1.3
	07 05	17.3	386	339	32	7.7	517.3	65	2.1	NNW	1.3
	08 08	26.2	185	158	63	7.2	518.0	45	8.0	WSW	1.0
9	06 20	2.9	507	604	19	7.0	516.5	88	0.5	NNW	2.1
	07 01	14.9	529	604	21	7.9	516.8	93	3.7	NW	2.1
	08 15	42.7	137	150	94	9.0	517.1	73	8.6	WSW	2.0
11	06 25	2.3	308	454	30	7.6	517.8	70	2.5	NNW	1.0
	07 08	2.3	364	389	43	10.8	517.9	60	6.0	W	2.0
	08 13	34.9	204	154	64	7.6	518.2	50	10.5	SSW	0.3
12	06 12	6.2	703	608	19	8.3	517.0	92	0.5	NW	0.0
	07 07	22.2	196	231	64	9.1	517.5	78	3.7	NNE	0.0
	08 08	29.8	137	119	103	8.8	517.7	57	8.6	SSE	0.0
13	06 17	1.7	871	960	20	12.2	516.0	49	0.5	WNW	2.0
	07 05	2.4	470	574	42	14.6	516.1	51	3.5	WNW	1.8
	08 10	23.2	336	270	69	13.9	516.9	38	8.0	SSE	1.3
14	06 18	4.3	672	920	23	12.2	516.2	43	0.5	NW	2.0
	07 05	23.7	434	570	35	11.7	516.8	48	2.3	NNW	2.0
	08 04	41.6	140	158	63	6.3	517.1	45	7.1	NE	1.0
15	06 20	4.8	484	661	14	5.3	516.2	63	2.5	NNW	0.0
	07 08	22.9	347	400	21	5.2	516.3	64	4.2	NW	0.0
	08 10	68.5	112	39	64	3.2	517.1	57	6.5	N	0.0
16	06 15	1.6	812	893	(26)	14.8	516.0	101	8.4	NE	1.9
	07 08	1.4	666	740	33	15.5	516.3	97	9.0	N	1.9
	08 06	1.4	420	531	35	11.1	517.0	80	10.7	N	4.0
20	06 30	32.6	624	641	10	4.2	518.8	86	2.5	WNW	0.0
	07 35	123.6	140	139	63	5.8	519.3	82	8.5	SSE	0.0
	08 12	98.1	95	192	82	7.8	519.7	65	10.5	SW	0.0
21	06 30	9.5	734	865	22	11.7	518.1	61	4.5	W	0.0
	07 12	54.1	638	700	21	9.4	518.6	58	5.7	NNW	0.0
	08 23	346.8	140	108	84	6.9	519.0	53	7.1	SSE	0.0
22	06 10	3.0	616	675	16	6.9	518.1	84	0.2	NW	0.0
	07 05	5.7	504	578	24	8.7	518.5	78	3.4	NNW	0.0
	08 12	55.8	188	123	80	8.3	519.0	61	9.2	SE	0.0
23	07 09	5.0	582	524	37	13.7	518.7	80	5.0	NNW	0.0
	08 10	112.2	140	116	125	10.7	519.3	67	9.5	SE	0.0
24	06 09	2.1	714	892	13	7.0	518.0	69	3.6	WNW	0.0
	07 10	1.9	535	626	28	10.8	518.5	64	7.0	NNW	0.0
	08 06	5.9	302	223	54	9.5	518.8	58	10.0	S	0.0
27	06 16	2.5	594	641	30	12.4	518.0	67	6.2	WSW	0.0
	07 05	2.2	588	578	32	12.4	518.2	63	7.5	WNW	0.0
	08 07	15.5	336	270	54	11.0	518.9	58	9.0	WSW	1.8
Means	06 17	5.8	638	713	16.2	8.9	517.3	72	2.3	.....	....
	07 10	22.0	436	477	31.5	10.0	517.7	69	5.1	.....	....
	08 10	63.3	199	182	64.0	8.1	518.2	57	8.7	.....	....

Note: Time of sunrise August 7, 1941, $06^h\ 10^m$; August 27, 1941, $06^h\ 00^m$; mean, August 7-27, 1941, $06^h\ 05^m$.

At all times when these observations were made there was a thick haze over the Huancayo valley as far as the eye could see. This layer of haze was estimated to be at a height of about one km and was probably due to the fact that there had been no rain to cleanse the air for a long time. This haze continued through the observations at 08^h but was usually more or less dispersed by 10^h. However, during the dry season at Huancayo there is always visible, in the daytime, a thin haze throughout the valley at a height of approximately one or two km.

It may be seen from the mean values of Table 1 or by an examination of the individual entries that at 06^h and at 07^h the negative conductivity is usually greater than the positive conductivity but the reverse relationship applies for 08^h. The mean value of the air-earth conduction-current is somewhat greater at 07^h than at either 06^h or 08^h, but this is of doubtful significance because the

means of this element for the days on which there occurred a well-marked progressive increase in nuclei-count throughout the period of observation showed no significant difference of this character. At least it is evident that there is no change in air-earth current either quantitatively or qualitatively comparable with the changes in the nuclei-count and the atmospheric-electric elements.

In brief, these simultaneous observations, particularly of nuclei-concentration, air-conductivity, and potential-gradient, show that the abrupt change between 06^h and 08^h in the electric elements is accompanied by a corresponding change in the concentration of nuclei; also that the ratio of positive to negative conductivity undergoes a marked increase between 07^h and 08^h on days when the other changes occur whereas there is no change in the air-earth current that seems to be significantly related to the abrupt change in either air-conductivity or potential-gradient. These observations seem consistent, therefore, with the explanation proposed by GISH for the unusual type of diurnal variation in air-conductivity and potential-gradient, for the small value at night of the ratio of positive to negative conductivity, and for the small average value of air-earth conduction-current observed at the Huancayo Magnetic Observatory.

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ATMOSPHERIC-ELECTRIC RESULTS FROM SIMULTANEOUS OBSERVATIONS OVER THE OCEAN AND AT WATHEROO, WESTERN AUSTRALIA

G. R. Wait

Simultaneous atmospheric-electric observations over the ocean and at a station on land provide a means for securing important information concerning the resistance encountered by the air-earth current at the station on land. During cruises of the Carnegie, previous to the seventh, atmospheric-electric observations at the observatories of the Department of Terrestrial Magnetism had not yet been initiated. During the seventh cruise not only were continuous records of the potential-gradient obtained aboard the vessel for the first time, but continuous records of both the potential-gradient and the conductivity of the air were secured at the Watheroo and Huancayo Magnetic Observatories. Conditions, therefore, favored the possibility of securing simultaneous atmospheric-electric data for fair-weather days over the ocean and at the Observatories. Atmospheric-electric data, secured simultaneously aboard the Carnegie and at the Watheroo Magnetic Observatory, are available for 42 fair-weather days during November and December, 1928, and January and February, 1929. Simultaneous mean hourly values of the potential-gradient and of the total conductivity (positive plus negative) were utilized to compute corresponding hourly values of the air-earth current for Watheroo. The conductivity (positive and negative) was observed daily aboard the Carnegie, with an occasional 24-hour series for determining the character of the diurnal variation. Assuming, as results seem to justify, that there is no diurnal variation in the conductivity over the ocean, hourly values of the air-earth current were derived from hourly means of conductivity and corresponding values of potential-gradient. Hourly mean values of the various elements for Watheroo and over the ocean are given in the form of diurnal-variation curves in Figure 1. The data have been divided into two groups, according to whether the days at Watheroo were smoky or free from smoke (non-smoky days).

The value at any station of the air-earth current (i), on the average, is proportional to the total potential (E) between the Earth and the upper layer from which the air-earth current flows, and inversely proportional to the resistance (R) of the intervening atmosphere, in accordance with Ohm's law; whence $i = (E/R)$. Assuming that, at any time, the value of E is the same at Watheroo and over the ocean, then $i_0R_0 = i_WR_W$ (the subscripts 0 and W refer to the values over the ocean and at Watheroo, respectively). The value of R_0, it is believed, may be regarded as constant through the day, for practically no diurnal variation appears to exist in the conductivity of the lower layer of air and there is no reason to expect one in the case of the conductivity of the higher layers. The value of R_W is proportional, therefore, to the ratio (i_0/i_W). Diurnal-variation curves of this ratio for smoky and non-smoky days are shown in Figure 1.

The resistance of the air near the ground is considerably increased when smoke is noticed at Watheroo. It seems of interest, therefore, to determine to what extent the resistance of the entire vertical column of the atmosphere is altered at such times. A comparison of the resistivity of the air for smoky (ρ_S) and non-smoky (ρ_C) days is given by the curves of Figure 2. The two values approach each other during daylight and separate as evening approaches, being farthest apart during the early morning; this is better shown in the curve for the ratio (ρ_S/ρ_C) of Figure 2. The ratio of the resistance of the total vertical column (R_S/R_C) at Watheroo for smoky to non-smoky days has somewhat similar characteristics to that for (ρ_S/ρ_C) but shows much smaller amplitude of variation. This indicates that the smoke affects the resistance of the entire vertical column of air to a much less extent than it does that near the ground. This would be expected if the smoke does not extend to great heights in the atmosphere.

The resistivity of the upper portion of the air-earth current circuit is believed to be relatively constant through the day. The diurnal variation in the total resistance R_W must, therefore, be due chiefly to a variation in the resistance of the lower part of the circuit. Since the resistance of the lower part of the circuit is equal to the product of the resistivity of the air and of its thickness, the variation in resistance may be due to a variation in either factor. It was assumed that the atmosphere through which the air-earth current at Watheroo flows is made up of two horizontal layers of air. The average resistivity of the upper layer of air was assumed to be constant through the day while that of the lower layer was assumed to be that derived from the conductivity-measurements near the ground. Assuming that the value of R_0 was constant through the day (equal to 10^{21} ohms), it is possible to determine the resistance of the upper layer of air and the effective thickness of the lower layer of air. If the resistance of the upper layer of air is r'_W, while the resistivity and thickness of the lower layer of air are ρ_W and h_W, respectively, then, since the

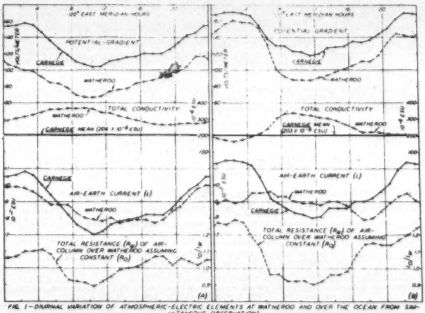

FIG. 1—DIURNAL VARIATION OF ATMOSPHERIC-ELECTRIC ELEMENTS AT WATHEROO AND OVER THE OCEAN FROM SIMULTANEOUS OBSERVATIONS.

CHARACTER	NOVEMBER 1928	DECEMBER 1928	JANUARY 1929	FEBRUARY 1929	TOTAL
(A) NON-SMOKY	8	5	7	5	25 DAYS
(B) SMOKY	4	5	3	5	17 DAYS

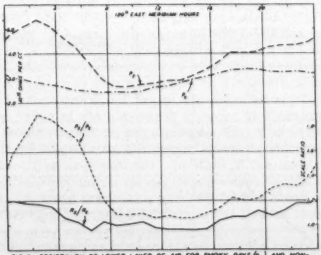

FIG. 2—RESISTIVITY OF LOWER LAYER OF AIR FOR SMOKY DAYS (ρ_S) AND NON-SMOKY DAYS (ρ_C), RATIO (ρ_S/ρ_C), AND RATIO OF RESISTANCE OF WHOLE VERTICAL AIR-COLUMN FOR SMOKY TO NON-SMOKY DAYS (R_S/R_C), WATHEROO, WESTERN AUSTRALIA

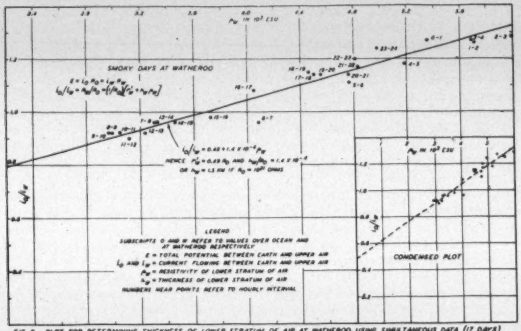

FIG. 3—PLOT FOR DETERMINING THICKNESS OF LOWER STRATUM OF AIR AT WATHEROO, USING SIMULTANEOUS DATA (17 DAYS) OVER OCEAN AND AT WATHEROO, NOVEMBER, 1928, TO FEBRUARY, 1929

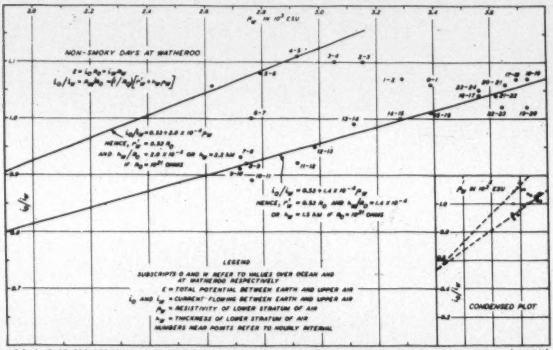

FIG. 4—PLOT FOR DETERMINING THICKNESS OF LOWER STRATUM OF AIR AT WATHEROO, USING SIMULTANEOUS DATA (25 DAYS) OVER OCEAN AND AT WATHEROO, NOVEMBER, 1928, TO FEBRUARY, 1929

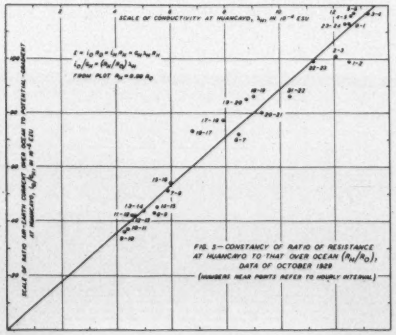
SCALE OF CONDUCTIVITY AT HUANCAYO, λ_H, IN 10^{-4} ESU
SCALE OF RATIO AIR-EARTH CURRENT DENSITY TO POTENTIAL GRADIENT AT WATHEROO, (λ_0/λ_W), IN 10^{-4} ESU

FIG. 5—CONSTANCY OF RATIO OF RESISTANCE AT HUANCAYO TO THAT OVER OCEAN (ρ_H/ρ_O), DATA OF OCTOBER 1929
(NUMBERS NEAR POINTS REFER TO HOURLY INTERVAL)

total resistance R_W is the sum of the two parts, $i_0/i_W = (r'_W + \rho_W h_W)/R_0$. Neither the value of r'_W nor R_0 would be expected to have a systematic diurnal variation. Regarding both values as constant, and plotting the ratio (i_0/i_W) against the resistivity ρ_W at Watheroo, a straight line should result. The plot for smoky days in Figure 3 shows that, except for a small scatter, a straight line is indicated. From the equation of the straight line given above, the value of the quantity (r'_W/R_0) is equal to the value of the ratio (i_0/i_W) extrapolated back to where $\rho_W = 0$. This value, for smoky days, is 0.49, and assuming that $R_0 = 10^{21}$ ohms, the value of r'_W is 0.49×10^{21} ohms. The average value of the ratio for smoky days is about 1.10; consequently, the upper layer represents about 45 per cent and the lower layer about 55 per cent of the total resistance for smoky days at Watheroo. From the equation of the straight line it is seen that the slope of the line is equal to the value of the quantity (h_W/R_0), which for smoky days is 1.4×10^{-4}; hence, if R_0 is 10^{21} ohms, $h_W = 1.5 \times 10^5$ cm or 1.5 km. This effective height to which the lower layer extends appears, from the graph, to be approximately constant through the day. In a similar way, values for the resistance of the upper layer and the effective thickness of the lower layer for non-smoky days can be derived. From the plot of the ratio (i_0/i_W) against the resistivity ρ_W for non-smoky days in Figure 4, the value for the ratio (r'_W/R_0) is 0.53, and since the average value of the ratio (i_0/i_W) is about 1.0 the resistance of the upper layer, on the average, is 53 per cent and that of the lower layer 47 per cent of the total resistance. From the slope of the curve, the effective height of the lower layer, during the greater part of the day, is 1.5 km--identical with the height for smoky days. During a few hours in the morning, however, the effective height appears to increase to as much as 2.2 km. It is not possible to say whether this is real or due to changes in some other factor assumed to be constant.

These results are of particular interest when viewed in connection with the results on the total resistance of a vertical column of air derived by GISH and SHERMAN [see 1 of "References" at end of paper] from the conductivity-measurements made aboard the balloon Explorer II on the stratosphere-flight of November 11, 1935. From the graph of those results connecting the resistance of the vertical air-column and height, one would expect to find 50 per cent of the resistance above a height two km in the atmosphere and 50 per cent below. Thus the present results are in almost perfect accord with those obtained by GISH and SHERMAN.

It is of interest to contrast the results from Watheroo on the height of the lower layer of air with results on the thickness of the lower layer of air at the Huancayo Magnetic Observatory in Peru. Data for October, 1929, for Huancayo and for the ocean, as obtained from the measurements of the Carnegie, have been utilized to obtain information concerning the thickness of the lower layer of air at Huancayo. When the ratio of the current (i_0) over the ocean to that (i_H) at Huancayo is considered in connection with the resistivity (ρ_H) of the lower air at Huancayo, no correlation is found. This implies that the large variation in the resistivity of the lower air at Huancayo produces no corresponding change in the resistance of the total vertical column of air there. This suggests that even though the resistivity-changes of the lower layer are large, the resistance-changes of the lower layer are small. This would naturally follow provided the thickness of the lower layer was small. In this case, one may write $i_0 R_0 = i_H R_H$. Since the air-earth current is equal to the product of the potential-gradient and the total conductivity, $i_H = G_H \lambda_H$ where G_H and λ_H represent the values of potential-gradient and conductivity at Huancayo, respectively; hence $(i_0/G_H) = (R_H/R_0)\,\lambda_H$. By plotting the ratio (i_0/G_H) against the conductivity λ_H, the value of the ratio (R_H/R_0) may be obtained. It is of interest to note that the curve passes through the origin, thus confirming the belief implied, as above, that the thickness of the lower layer of air is very small. The slope of the curve gives the value of the ratio (R_H/R_0) as 0.89, indicating that the resistance of the vertical column at Huancayo is 89 per cent of that over the ocean. In view of the high altitude of the Observatory (3.3 km), this value of the resistance is much greater than was to be expected. From the curve of resistance between the Earth and a point in the atmosphere with distance above sea-level [1], the total resistance of a vertical column of air down to a point 3.3 km above sea-level appears to be only one-third that of a column of air down to sea-level. In other words, short-circuiting the lowest 3.3 km of air should have the effect of increasing the current by a factor of 3.3. The value of the air-earth current at Huancayo, however, is not 3.3 times that over the ocean as one would expect on the above basis. The decreased current, if one assumes no loss of current during its passage from the upper levels to the ground, requires the existence of an extra resistance in the air over Huancayo. In view of the small vertical thickness of the lower layer of air there, the extra resistance cannot be confined to this layer. The extra resistance must be situated, therefore, in some layer at a greater height above the ground. The resistivity of this layer must be considerably greater than that of the lowest layer.

It seems probable that the extra resistance-layer may lie immediately above the lowest layer of air as evidenced by the following considerations: It is observed that the ratio of positive conductivity (λ_+) to negative conductivity (λ_-) at Huancayo is unusually small and at times is less

than unity, which suggests the existence of an unusually small positive, or at times a negative, space-charge in the lower layer of air. This fact is consistent with an increase in resistance with height and indicates the presence of a bank of condensation-nuclei at a height not far removed from the ground-layer. Further, it appears necessary, as pointed out by GISH [2], to account for the observed change in conductivity of the lower layer of air during the early morning through the existence of a dense layer of nuclei immediately above the lower layer of air. The high value of the conductivity, occurring as it does during the night, appears to be the result of the formation of a stable layer of air containing but a few nuclei near the ground. Later in the day, the conductivity rapidly diminishes to relatively low values which is explained by nuclei being brought by convective processes into the lower layer from the adjacent upper layer. An increase in the nuclei-content with height has actually been found at Palo Alto, California, by YUNKER [3] as a result of measurements at the two levels of 0.5 and 20 meters. The existence of such a layer at Huancayo will account for the unexpectedly low air-earth currents measured there, the small value of the ratio of positive to negative conductivity, and the unusually large diurnal variation in conductivity of the lower layer of air.

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[2] Carnegie Inst., Year Book No. 37, 1938.
[3] Terr. Mag., v. 45, pp. 121-126, 1940.

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OVERCOMING THE HUMIDITY-PROBLEM AT A TROPICAL MAGNETIC OBSERVATORY

John Hershberger

No doubt every one here knows where Puerto Rico is, though I scarcely did until I was about to go there last summer. Since then I have found that others have the same wrong impression as to its location that I had. In case any one here is likewise misinformed, let me point out that Puerto Rico is about 1,750 miles due south of Nova Scotia, farther east than we often realize.

Puerto Rico is also a place that is very damp. It pours when it rains, and it rains much of the time. At the same time the temperatures are high, and as a result the humidity is kept near the saturation-point. It is so damp that newspapers do not rattle when handled, but are limp like rags. You can press clothes without moistening them, and they will still be excessively damp.

This climatic condition has presented one of the most serious problems in connection with operation of the Magnetic Observatory located on the Island. Corrosion, rust, and fungus have been very active in hindering proper functioning of the instruments. For some years the variometers were fitted with drying tubes, and were made as nearly air-tight as possible by sealing them with paraffin. But the moisture still got in, and the repeated renewing of the drying tubes necessarily resulted in disturbance to the instruments.

A little more than a year ago a nonmagnetic metal cover was designed to fit on the pier, covering all three variometers. The cover is rectangular in shape, like a large box without a bottom. It rests in a metal channel about one-half inch wide and one-half inch deep, which is sealed onto the pier-top with plaster of paris all around. The channel is filled with heavy grease, so as to make an air-tight seal between the cover and the pier. A small breather-opening is provided on one side of the cover, and is connected to two drying tubes in series on the outside. Except for this opening, the cover is air-tight. A window of optical glass at one end, tilted slightly to prevent stray reflections, permits light to pass through for photographic recording. Several large dishes of calcium chloride were placed on the pier just before the cover was put into position. This keeps the air inside the cover as dry as Arizona.

The instruments gave promise of improved performance after the cover was installed, but their behavior was somewhat erratic, due probably to the sudden change in the condition of the air surrounding them. The Z-variometer in particular acted strangely, as though the center of gravity of the recording magnet were shifting. While the real cause of this performance may never be known, it seems reasonable to suppose that some foreign particle may have been in

contact with the pivots, but remained soft enough because of the dampness to have no noticeable effect until it hardened from drying out after the cover was put on.

In July and August, 1941, the entire magnetograph was replaced with newly reconditioned equipment. This included a la Cour Z-variometer, and Toepfer D- and H-variometers, all somewhat modified. Although the la Cour Z-variometer is designed to operate with the recording magnet in a vacuum, the chamber was not evacuated, since the instrument was to be placed under the air-tight cover. The valves were left slightly open, so that the pressure inside the chamber would remain the same as that of the outside atmosphere. Otherwise it was feared that under certain conditions the inside pressure might be higher, which could easily disturb the adjustment of the instrument. A temperature-compensating magnet was mounted underneath the variometer.

The D- and H-variometers were fitted with la Cour-type suspensions and with three-face prismatic mirrors, so as to provide reserve-spots both above and below the regular spots. The H-variometer has a temperature-compensating magnet, but no sensitivity-control magnet. The desired sensitivity was obtained by choosing a suspension-fiber having the proper torsion-constant, which had been determined previously in an independent measurement. No control or compensating magnet of any kind is used on the D-variometer.

These are the variometers which were available at the time it seemed in order to make the new installation. Naturally they were not designed to fit under the air-tight cover, nor was the cover designed for these instruments. It was inevitable that some difficulties would be encountered in fitting the new variometers to the cover. Three principal problems arose in this connection. In the first place, the cover was not high enough. The D-variometer is quite tall from the lens up, and the new compensating magnet has made the Z-variometer tall from the lens down. Since all three lenses had to be at the same height in order to avoid parallax, this made the total height greater than that of the cover. At first it was planned to raise the cover by building an auxiliary base under it, but then it developed that the ceiling of the room was too low to permit this. The problem was finally solved by cutting a hole into the pier-top under the Z-variometer, into which the compensating magnet could project. This permitted lowering all the variometers sufficiently to go under the cover on its original base.

In the second place, the cover was not long enough. The focal lengths of the Z- and H-lenses would have required these two variometers to stand farther apart than the length of the cover would permit. The way we solved this problem was very simple. We simply set the instruments as near the ends of the cover as possible, and if the spots did not focus sharply that was their own hard luck. Actually, the quality of the spots was not seriously impaired.

In the third place, the cover was not wide enough. More specifically, the glass window was not wide enough to accommodate all the light-beams. With the recording lamp in the usual position at the side of the recorder-box, the situation was quite hopeless. A solution was found by borrowing an idea from some of the newer seismograph-recorders and mounting a 45° mirror on the front of the recorder-box, under the middle of the shutter-opening. The lamp was directed toward the mirror, which reflected the light through the window to the recording mirrors.

With this arrangement, and with very careful placing of the variometers, we succeeded in getting all the beams through the window except that of the time-flasher. No flasher had been used in the former installation, time-marks having been made by another method. The new flasher-system was left entirely outside the cover, and as a result the hour lines do not cover quite the entire width of the magnetograms.

Great care was exercised in adjusting the new instruments so as to prevent parallax between recording spots and time-lines. This of course required that all the recording beams, as well as the flasher-beam, would have to be at the same height. Otherwise the flasher-mirror could probably have been placed inside the cover.

An interesting demonstration of the effectiveness of the metal cover in keeping out moisture was afforded when the cover was removed for the purpose of making the new installation. Three dishes piled full with calcium chloride lumps had stood under the cover for some months, and only the surfaces of the lumps had become slightly wet. When the cover was removed and the dishes exposed to the air in the room, the lumps melted down like ice-cream in an oven.

A problem not related to humidity results from the large annual change in declination in Puerto Rico. The total change since the former installation was made had been about 1°3. This fact complicated the problem of resetting the scale-value-deflector holders to adapt them to the

new installation. It also means that the holders will need to be moved again after a few years, and that orientation-adjustments of the recording magnets will need to be made from time to time.

It appears that the air-tight cover may be the answer to the humidity-problem, so far as the variometers are concerned. While the instruments are less accessible, this is sometimes a good thing, as it provides a certain amount of protection against accidental disturbance. The cover has not been in use long enough for a thorough test, but we are maintaining a state of suspended optimism.

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MAGNETIC WORK OF THE UNITED STATES COAST AND GEODETIC SURVEY FROM APRIL 1941 THROUGH MARCH 1942

O. W. Swainson

Magnetic surveys

Most of the magnetic observations of the past year were directly related to military purposes, and consequently cannot be discussed at this time. They were scattered along the East, Gulf, and West coasts, with a few in the Eastern States.

In these national-defense magnetic surveys stress was laid on obtaining the vertical intensity (Z). This was a departure from former surveys where Z was more or less incidental. One of the results was to emphasize the lack of suitable instruments for making absolute measurements of this element. Considerable study in cooperation with other agencies is being given to the problem with some prospect of improving the situation. Two experimental instruments were tested at Cheltenham, one being developed by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington and the other by the Geophysical Section of the Geological Survey.

Field-observations were begun along the coastline of the Caribbean Sea in order to issue a new isogonic chart of that area, and to make some of the ten-year repeat-observations formerly made by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. Transportation was mainly by airplane. The project offered an excellent opportunity to obtain comparisons at many Observatories as the instruments were standardized at Cheltenham (Maryland), San Juan (Puerto Rico), and Vassouras (Brazil). Another standardization will be made at the Observatory at Teoloyucan, Mexico. Observations were completed in Cuba, Dominican Republic, Haiti, Puerto Rico, Antigua, Trinidad, and British Guiana. It is hoped that means will be found to complete this repeat-station program throughout all of South America.

In cooperation with the Navy Department an investigation was made of the effects on compasses in airplanes flying over disturbed areas. It was found that no appreciable effect was discernible over Wilmington, Delaware, but over Port Snettisha, Alaska, where an anomaly of 60° is indicated on the surface, departure from normal of 5° was noticed at an altitude of 3,000 feet, and 25° at 1,000 feet.

Observations were made in the past year as listed in Table 1.

Observatories

The five Magnetic Observatories of the Bureau continued operation without interruption.

Cheltenham, Maryland--The international standard observatory at Cheltenham, Maryland, was used almost continually by personnel of the Army, Navy, and other National Defense organizations for standardizing and testing special equipment. The standard earth-inductor was changed from CIW No. 6 to CIW No. 48.

Honolulu, Territory of Hawaii--The Honolulu Observatory has continued in operation despite the war activities on the Island. Arrangements were made to install electric power.

San Juan, Puerto Rico--A modernized and reconditioned magnetograph was installed, the Z being a la Cour, and H and D Eschenhagen. It was covered with an air-tight cover to protect it from the humidity. Intercomparisons with the Cheltenham Observatory were made with field and

Table 1--Magnetic stations April 1941 to March 1942

State or region	Repeat-stations				Other stations	Totals
	Old		New			
	D only	Complete	D only	Complete		
California	...	2	...	...	1	3
Maine	...	...	...	...	6	6
Maryland	...	...	...	2	...	2
North Carolina	...	...	3	...	...	3
South Carolina	1	...	...	1	...	2
Vermont	...	...	...	...	9	9
Virginia	...	2	1	...	1	4
Washington	...	...	...	...	9	9
Alaska	...	...	...	...	30	30
Midway Island	...	...	...	...	5	5
Hawaii	...	...	...	...	2	2
West Indies	1	6	...	5	5	17
South America	...	2	...	3	...	5
Philippine Islands	...	...	...	...	19	19
Totals	2	12	4	11	87	116

observatory earth-inductors. Arrangements for building a new absolute building were completed.

Sitka, Alaska--The old magnetographs were continued in the temporary building due to the uncertain conditions of transportation and war hazards at Sitka. A new metal pendulum-clock was installed.

Tucson, Arizona--Careful intercomparisons were made between Tucson and Cheltenham Observatories with both field and observatory earth-inductors. The remodeled and reconditioned la Cour magnetograph described at the last meeting of the American Geophysical Union was installed in the new variation-building and was operated for many months simultaneously with the instruments in the old building. Grams obtained from the two sets of instruments during a severe magnetic storm were identical. This indicated that the partial underground installation of the new instruments had no adverse effects. Pier-differences also were determined. Improved time was obtained with a new master metal pendulum-clock.

Cooperative work

The Division has maintained the previous close cooperation with other organizations which is necessary for best results in the measurement and study of such a world-wide phenomenon as geomagnetism. The principal cooperation with the Carnegie Institution of Washington was as follows:

(a) Use of that Institution's sine-galvanometer and earth-inductors at the Cheltenham Observatory
(b) Operation at Cheltenham of the cosmic-ray meter of the Committee on Coordination of Cosmic-Ray Investigations
(c) Loan by the Institution of field earth-inductors
(d) Assignment of three-hour-range indices (K-figures)
(e) Atmospheric-electric and earth-current measurements at Tucson

The Mountain States Telephone and Telegraph Company and the American Telephone and Telegraph Company also cooperated in the measurements of earth-currents at the Tucson Observatory.

The URSIgram messages formerly distributed through the cooperation of Science Service and the Navy Department were discontinued in December.

The International Boundary Commission made magnetic observations for this Bureau along the Maine-Canada Boundary, thereby obtaining valuable information for that critical area.

The LOUISE A. BOYD Expedition made magnetic observations which are valuable in the compilation of charts of the waters adjacent to Greenland.

Office work

The Work Projects Administration Office maintained in New York City continued to process

observatory-results relating to war work and the Polar Year. A similar project in San Juan, Puerto Rico, did some work on that Observatory's records, but was unsatisfactory. The publishing of observatory-results has gained somewhat but still is five years in arrears. The furnishing of magnetic data for nautical and aeronautical charts has expanded fourfold. The isogonic chart for 1940 of the United States was issued, and an addendum prepared for inserting in the issue of 1935 of "Magnetic declination in the United States" explaining how to use the tables of 1935 in connection with the chart of 1940. This was in lieu of an issue in 1940 of the publication. The isogonic chart of Alaska for 1940 was issued, and the preparation of the publication "Magnetic tables and charts for Alaska for 1940" was nearly completed. After consultation with the users of our weekly lists of one-half day character-figures, these lists were discontinued as the new K-figures give better information.

U. S. Coast and Geodetic Survey,
Washington, D. C.

RESEARCHES IN TERRESTRIAL MAGNETISM AND ELECTRICITY AT DEPARTMENT OF TERRESTRIAL MAGNETISM, CARNEGIE INSTITUTION OF WASHINGTON, FOR THE YEAR APRIL 1941 TO MARCH 1942

J. A. Fleming

Since many fundamental researches in geomagnetism and geoelectricity depend on observations from all parts of the world, international collaboration is necessary for the effective pursuit of such studies. During the period under report, however, many of the countries from which in normal times the required data are received have been involved in war and have been unable to furnish observational material. As a consequence, the work of the Department has been largely confined to further detailed study of the accumulated records on hand.

Throughout the United States, many specialists were called to develop the scientific aspects of problems concerned with national defense. In accordance with the action of the Trustees of the Carnegie Institution of Washington, the services of the regular scientific and administrative personnel and the use of equipment, site, and buildings have been contributed without cost to the Government. Several of the regular staff were also on leave of absence at Government laboratories. On the other hand, a large number of investigators, including physicists, engineers, assistants, and technicians--many on leave from universities and commercial organizations--have been engaged at the Department to assist in developing urgent projects submitted by the Navy and Army through contracts with Governmental agencies. Despite these demands it was possible to maintain a skeleton staff in all the sections so that the regular work was carried on without too serious interruption.

Geomagnetic investigations

An investigation based on selected polar-year stations was made of the frequency of occurrence of geomagnetic bays. The annual variation in frequency shows a double wave with maxima near the equinoxes. The average daily frequencies vary in a marked way with geomagnetic latitude. Near the center of the auroral zone the frequency is practically independent of time of day while at the auroral zone it depends closely on local geomagnetic time with negative bays predominating and having a maximum frequency at 01^h local geomagnetic time (LGT) and positive bays at 18^h LGT. In low and middle latitudes positive bays predominate with maximum frequency at 24^h LGT, negative bays reaching a maximum near 16^h LGT. Mean three-hour vector-components of the field of bays showed rotation depending on time of day. On the basis of these data an electric current-system of bays was derived for an estimated height of 150 km in auroral regions. This current-system is further shown to afford a possible explanation of the observed latitude-variation of frequency and amplitude.

The annual variation of geomagnetism at Polar-Year stations, as shown by the monthly departures from annual means, was examined. An electric current-system which could reproduce the field shows a variation in intensity characterized by a double wave, with maxima at the equinoxes, symmetrical about the geomagnetic axis and equator, and a single wave with maximum amplitude at the solstices, opposite in time-phase on either side of the equator. The comparatively large variation in polar regions produces marked seasonal changes in the form of the polar current-system of geomagnetic disturbance.

All the measurements on the CIW primary magnetic standard were made and the analyses of

the results were nearly complete. They indicate that the required accuracy has been attained so that the coil-constants can be specified to approximately one part in a million. The actual instrument was not quite finished because of temporary assignment of personnel to other urgent matters.

CHAPMAN continued his notes on isomagnetic charts. Note V, which concluded the first connected group of papers, dealt with the occurrence of local dip-poles. CHAPMAN showed that local magnetic dip-poles occur in pairs or groups of pairs and illustrated the nature of isomagnetic lines and magnetic meridians in the simpler cases. He also showed that the local magnetic disturbance due to a single magnetic pole, if sufficiently intense, can produce one pair of dip-poles, and that if the disturbance is due to the field of a sufficiently intense local dip-pole, there may be either one or two local pole-pairs according to the orientation of the dipole. If the dipole-field is due to magnetization induced in a roughly spherical mass of magnetite or iron pyrites, by the existing normal field, the necessary susceptibility of the mineral, if it is to produce local dip-poles, is shown to depend on the ratio of its radius to its depth, and on the local value of the normal horizontal intensity. He suggested a classification of pole-pairs according to this value of horizontal intensity and the distance between the poles of a pole-pair.

The sixth paper, which is the first of a further group of three, dealt with the earth-air electric currents and the mutual consistency of the isomagnetic charts of horizontal intensity (H) and declination (D). It was pointed out that atmospheric-electric observations indicate that the electric currents crossing the Earth's surface are too weak to have an observable effect on the distribution of the geomagnetic field which should therefore (to a high degree of accuracy) be derivable from a scalar potential. Of the various methods of examining the question, that due to SCHUSTER of calculating the vertical component of the curl of the field at particular points is found to be the most generally useful. A new formula is given for calculating the curl (i) directly from the isomagnetic charts for D and H. The new process was applied to the Admiralty charts for 1922 and the error of estimation of the curl, or the resulting inferred vertical current-intensity, examined. It is suggested that when the new charts of D and H are constructed the value of i should be taken as zero (on the atmospheric-electric evidence) and the mutual consistency of the charts should be tested and adjusted by the methods developed.

These theoretical discussions indicate possible improvements in the construction of future isomagnetic charts.

Observatory-work

The Observatories of the Department at Huancayo, Peru, and Watheroo, Western Australia, continued their regular geophysical programs, including determinations of geomagnetic, geoelectric, and meteorological elements.

Cooperative work was continued as follows with various Observatories: Atmospheric-electric and geomagnetic programs at Apia, Samoa (atmospheric-electric recordings discontinued December 31, 1941); atmospheric-electric and earth-current programs at Tucson, Arizona; maintenance of international magnetic standards at the Cheltenham Magnetic Observatory of the United States Coast and Geodetic Survey, and, through loan of instruments, Cape Town and Hermanus Observatories (South Africa) and the Royal Alfred Observatory (Mauritius).

A magnetic and ionospheric observatory was established at College, Alaska, in cooperation with the University of Alaska, in connection with the extension of investigation of correlations of geomagnetic, ionospheric, and auroral work in polar regions. The required absolute equipment was standardized at Cheltenham Magnetic Observatory and the Polar-Year buildings were rehabilitated and a complete la Cour magnetograph was placed in operation. A CIW automatically recording multifrequency equipment and a special automatically recording auroral camera are included in the equipment.

Survey-work

Because of limited available personnel and National-Defense activities, continuation of observations to determine secular-variation and new distribution-data has been chiefly effected through collaborative arrangements with other organizations. In Africa cooperative work has been continued with the British East African Meteorological Service. On the basis of stations occupied, together with previous data at CIW stations, a provisional isogonic map of Uganda Protectorate was prepared for epoch February 1941. In Australia the Aerial, Geological, and Geophysical Survey of Northern Australia continued its cooperative work, the primary object being to reoccupy stations for obtaining data concerning secular variation. The Department of Scien-

tific and industrial Research of New Zealand, having made extensive intercomparisons with CIW magnetometer 27 at Amberley (Christchurch) Observatory, is undertaking a resurvey of that country. The plan is to observe at about 12 secular-variation stations previously occupied by the Carnegie Institution of Washington and at new stations throughout the length of the country beginning at the extreme south, after which the survey will be extended on both sides according to the season. Provisional estimates of the secular change in declination indicate that the rate at the northern stations of the South Island is less than at the southernmost stations.

The United States Antarctic Expedition, in the equipping and training of personnel for which the Department cooperated, returned to the United States in May, 1941. Two of the physicists of the Expedition were assigned to the Department to complete the reduction of the magnetic records and the compilation of the auroral data. In reducing these observations special attention will be given to the relation between auroral occurrence and magnetic disturbance. It is also hoped that some correlation can be made with the many radio observations taken during auroral displays, as well as at times when no aurora was visible.

The LOUISE A. BOYD Arctic Expedition of the National Bureau of Standards, in the arrangements of which the Department cooperated, sailed from Washington, D. C., June 11, 1941, and returned to the United States, November 3, 1941. In the course of the Expedition, magnetic observations were obtained at 14 stations in Newfoundland, Greenland, Devon Island, and Baffin Island. Ionospheric characteristics as determined by special radio measurements, auroral manifestations, and measurements of ultra-violet intensities were also included in its program.

Geoelectrical investigations

On the basis of average hourly values of air-earth current determined by the indirect method at College, Alaska, for 11 months in 1932-33, it was shown that, because of the usual negative correlation between gradient and conductivity, the values of current derived from these elements if averaged over periods greater than one hour will generally exceed those derived from values averaged over hourly intervals. The maximum excess in an hourly mean value is 29 per cent. The effect upon the amplitude of the diurnal variation would be approximately 25 per cent of the true variation in current. The maximum excess in the daily mean values at College would be approximately 50 per cent, whereas at other stations it may often be greater than this. These considerations suggest that, because of the difficulty of computing exact values, the indirect method of measurement may be expected to yield greater values of earth-air current than the direct method.

Investigation of nuclei of condensation from various sources shows that different nuclei vary distinctly in their rate of decrease with time. There is some indication that entities not observed with an Aitken nuclei-counter serve for formation of large ions. Further investigation of the behavior of the Aitken nuclei-counter shows that, contrary to claims which have been published, the total nuclei-count, including all expansions which bring down nuclei, is independent of the ratio of expansion from very small ratios up to 1.35.

For the first time, simultaneous atmospheric-electric data over the ocean and at a land-station have been compared. This comparison permits the deduction of the diurnal resistance through which the air-earth current at Watheroo flows. The resistance was found to vary appreciably through the day, the minimum occurring shortly before noon being some 20 per cent less than the maximum in the case of non-smoky days at Watheroo and some 30 per cent less than the maximum on smoky days. The variation in resistance can be fully accounted for on the basis of two stratified horizontal layers in the atmosphere. The resistance of the upper layer is approximately one-half the total and is constant throughout the day while that of the lower varies in a manner identical with that found from the conductivity-measurements at Watheroo. The effective height of the lower layer is about 1.5 km and is constant through the day except for a few hours in the morning on non-smoky days when it rises to about 2.0 km. The thickness of the lower layer at Huancayo was found to be much less than that at Watheroo, in fact practically zero. The total resistance at Huancayo is essentially constant through the day and is about 89 per cent of that over the ocean.

From consideration of further evidence, it appears that conclusions previously reached that the air-earth current at Watheroo is essentially as great during smoky as during non-smoky weather requires modification. To secure additional evidence on this point, data for the Februaries during the period 1924-1934 were considered, since February is the smokiest month of the year at Watheroo. From all the evidence now available it seems that the current during smoky weather is, on the average, less than the current during non-smoky weather, thus suggesting that

the resistance is greater during the smoky weather. This, in turn, suggests that the smoke is distributed to considerable heights in the atmosphere.

From data on small and large ion-content of occupied rooms it was deduced that the large ions were sent into the room at a rate corresponding to about 280×10^6 per breath (assuming two people in the room). This number is in good agreement with previous results. The recombination-coefficient comes out about 1.2×10^{-6}, indicating a relatively small particle.

Ionospheric investigations

Continued observation of the ionosphere at Huancayo and at Watheroo has now yielded sufficient homogeneous data to permit more detailed systematic analysis of electrification of the outer atmosphere than has ever been possible. These data are especially valuable for predicting the performance of radio-wave propagation over long distances.

As the nature of the ionization in the outer atmosphere of polar regions presents a major problem in investigation of the Earth's magnetism and its variation, the Department is undertaking its investigation through the establishment, in cooperation with the University of Alaska, of an observatory on the University Campus in the zone of maximum auroral frequency. All known methods of studying the high atmosphere are being brought to bear in this investigation, including magnetic, ionospheric, and auroral observations.

Publications

The activities of the Department are set forth in greater detail in Year Book No. 40 of the Carnegie Institution of Washington. A few of the principal papers published during the last year are listed below.

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S. CHAPMAN, Greenwich frequency-statistics of geomagnetic disturbance, Terr. Mag., v. 46, pp. 385-400, 1941.

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B. CYNK, Some relationships in the fields of geomagnetic storms, Terr. Mag., v. 46, pp. 431-433, 1941.

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O. H. GISH, Terrestrial electricity in relation to geomagnetism, Proc. Amer. Phil. Soc., v. 84, pp. 187-204, 1941.

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K. L. SHERMAN, Comparison of methods for computing air-earth current, Terr. Mag., v. 46, pp. 401-407, 1941.

G. R. WAIT and O. W. TORRESON, Atmospheric-electric results from Watheroo, Western Australia, for the period 1924-1934, Terr. Mag., v. 46, pp. 319-342, 1941.

A. WALTER, Preliminary results of a magnetic survey in Uganda Protectorate, February-March 1941, Brit. East African Met. Serv., Ser. A, No. 1, 9 pp., 1941.

Department of Terrestrial Magnetism,
Carnegie Institution of Washington,
Washington, D. C.

AMERICAN GEOPHYSICAL UNION

TWENTY-THIRD ANNUAL MEETING

SECTION OF OCEANOGRAPHY

REPORTS AND PAPERS

Washington, D. C.
April 3, 1942

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THE OCEANOGRAPHIC WORK OF THE HYDROGRAPHIC OFFICE DURING THE PAST YEAR

G. S. Bryan

I am glad that, despite the War, we have taken a short time off today from our busy duties to meet and exchange ideas on the many phases of science represented by the American Geophysical Union. Now, more than ever, are such meetings essential in that something may come to light which will prove of value to our country in achieving victory.

The oceanographic work carried out by American governmental agencies and private institutions since the "Union" was founded has proven of great value to the mariner. Today, he has at his disposal not only accurate charts but also the equipment which permits him to determine the track of his vessel with reasonable accuracy. The money that has been used in research has given magnificent returns in saving of life and property.

The Hydrographic Office is proud of the work it has accomplished in this specialized field of engineering. It was the Navy that developed sonic sounding-gear and the Hydrographic Office has consistently made the greatest use of this instrument. Now that we are at war, it has been necessary to curtail certain of its oceanographic activities in order to concentrate all of its efforts in the surveying of vital areas and in the production of surface- and air-charts for the Navy and for the other branches of the armed forces. For over a year, the Hydrographic Office has been operating on a 24-hour basis in order to provide the Fleet with world-wide chart coverage. Our job is a big one, for it involves the correction and printing of over 3,900 charts and 130 publications covering all the navigable waters of the globe.

In addition, our air-navigation charts today cover a wider field due to the rapidly changing condition of the theater of war. The planning of new charts has been done with forethought for, being a military organization, the staff of the Hydrographic Office has been preparing for the day when the United States of America would again be called to fight in the cause of liberty. For many months our Reproduction Plant has been laboring to meet the ever-increasing demands for charts. The monthly average of one million copies equals twice the yearly average of production of a few years ago, and the Hydrographic Office is now the leading chart-producing agency in the world. This last quarter, 30 new navigational charts were published. In addition, a large number of special aviation-charts were produced. These charts, specially designed for the use of aviators, at last fulfill the special requirements of the air-pilot, not only on account of the manner in which important features are portrayed, but also in the size and binding utilized.

The Hydrographic Office continues its surveys despite the War, for, in keeping with its tradition of over 100 years, all of its surveys are of areas of commercial and strategic importance. In this emergency, however, we believe that time is the most important factor under consideration. Therefore, the Hydrographic Office is not wasting any of it in "the pursuit of an impossible perfection". The ship-shore method of triangulation, where the cuts to the intersection-station are controlled by radio, is being utilized more and more. An accuracy of between second and third order is being achieved at a fraction of the cost of surveys in which all of the triangulation-points are located on land. It is believed that this method, which has proven so successful in certain surveys conducted by the Hydrographic Office during the last three years, should be utilized in all hydrographic surveys where the coasts are abrupt and the terrain mountainous and inaccessible and where conditions allow operations only for a limited time each year. An innovation of this method, using helium-filled balloons, has proven economical and expeditious in the location of points of control for photogrammetric compilations by the United States Army Engineers. Both methods should be studied and utilized in order that areas being mapped for defense may be completed without delay. The information is needed now and those that are fighting this war are not concerned with minute accuracy of detail. I do not wish to convey the idea that our standards of accuracy should be permanently lowered; I am trying to be practical at a time when maps are sadly lacking. The picture is changing so rapidly that we do not know when or where our forces may be called to go into action. Let us all do our share to expedite the work entrusted to us.

Despite the lack of time and the restrictions of war, the Hydrographic Office continued to receive very valuable sonic sounding-data from Naval vessels and from private shipping companies. These data are being incorporated on affected charts as fast as opportunity permits. The forethought of this Office in initiating a program of oceanic soundings several years ago has brought

very fruitful results in that many vital areas have been adequately covered.

Outstanding among the many contributions received during the past year is the magnificent work which Dr. SHEPARD of the University of Illinois and his associates were able to carry out in the Gulf of California and adjacent areas. Under his direction, considerable sounding-data were compiled which will prove of value to the Navy.

Within a few months, a chart and pilot of the Antarctic Continent will be ready for issue. No better authority than Commander ROBERT A. J. ENGLISH of the United States Navy could have been found to prepare this most comprehensive presentation of Antarctica. As Commanding Officer of the Bear on the Second BYRD Antarctic Expedition, and as Executive Secretary of the United States Antarctic Service, he gained an enviable reputation for his thorough knowledge of the history of the explorations that have been carried out in that vast area since WILKES' memorable discovery. This chart of the Antarctic will be up to date in all respects and, in addition, will show the bathymetry developed from the many soundings taken by the various expeditions conducted under the leadership of Admiral BYRD.

The project of the Hydrographic Office for the evaluation of ocean-current and sea-surface temperature-data covering the entire globe, which was successfully concluded last year, is proving of inestimable value in the problems arising from the War. While this activity cannot be discussed, it may be mentioned that every ship's lifeboat now carries a copy of the Hydrographic Office Pilot Chart, covering the waters traversed, for use in case of emergency. The utilization of the oceanographic information shown on these charts relative to winds and currents may result in the saving of many lives at sea in case of disaster.

Due to the confidential nature of most of the work being conducted by the Hydrographic Office, my remarks today have had to be more or less general in scope. After this war is over, certain details may be revealed which may prove of interest to you.

The Hydrographic Office has always been anxious to cooperate in the matter of scientific work. At the present time only such work as promises to contribute to the successful conduct of the War can be undertaken. On the conclusion of hostilities, however, it is hoped that we may be able to undertake other research work which comes more under the heading of peace-time activities.

U. S. Hydrographic Office,
Washington, D. C.

OCEANOGRAPHIC WORK OF THE UNITED STATES COAST GUARD IN THE WESTERN NORTH ATLANTIC IN 1941

R. R. Waesche

The ice-season of 1941 was similar to that of 1940 in that there was an almost complete absence of ice in the vicinity of the Grand Banks of Newfoundland. For this reason no ice-observation cruises were made by the patrol-cutters and only the oceanographic vessel of the International Ice Patrol Force was engaged in operations in this region during 1941. This vessel, the 125-foot U.S.C.G. Cutter General Greene, made three current-surveys of the Grand Banks region during the period from March 29 to July 14. From these surveys three dynamic topographic charts were constructed. In this work 195 oceanographic stations were occupied, the serial observations of temperature and salinity usually extending from the surface to a depth of about 1,400 meters where the depth of water permitted, although the topographic charts were referred to the 1,000-decibar surface. A short post-season cruise was made in the southern part of the Labrador Sea between July 21 and August 3. During this cruise 12 oceanographic stations with closely spaced observational levels, from the surface to a depth of 150 meters, were occupied in the immediate vicinity of an iceberg off the Strait of Belle Isle. An additional 24 stations were occupied, from the surface to as near bottom as was practicable, along a section from South Wolf Island, Labrador, to Cape Farewell, Greenland. A list of 267 sonic soundings taken along this section during the post-season cruises of 1940 and 1941 has been corrected, tabulated, and supplied to the United States Hydrographic Office. Other incidental data collected, both during the season and post-season cruises, consisted of barograms and sea-water-surface thermograms. On all cruises a program of bathythermograph observations supplemented the usual reversing-thermometer observations of temperature, through cooperation with the Woods Hole Oceanographic Institution, with GILBERT OAKLEY of that Institution as observer.

Another cooperative project undertaken jointly by the United States Coast Guard and the Woods Hole Oceanographic Institution was the preparation of a batch of standard sea-water. Special equipment was designed and built for subsurface collection of large quantities of water. The water was obtained from depths of 400 to 800 meters below surface in the slope-water on the edge of the Gulf Stream. Upon collection it was filtered and stored in glass-stoppered carboys for a period of about nine months. It was then mixed in a large glass-lined crystallizing dish and sealed into pyrex-glass tubes. Its chlorinity has been compared against Copenhagen standard water of the batch P_{15}, and against sodium chloride, and the American standard water is now ready for distribution. Further work on interpretation of its chlorinity in terms of pure silver is planned for the future.

The scientific work was under the direction of Principal Physical Oceanographer FLOYD M. SOULE. Throughout the year, but particularly in connection with the chemical work involved in the preparation of the American standard sea-water, which was his special contribution, Associate Physical Oceanographer CLIFFORD A. BARNES participated in the work described. United States Coast Guard Bulletin No. 31, by SOULE and BARNES is in preparation. This Bulletin deals with the results of the work of 1941 just outlined. The oceanographic section of this Bulletin may be partially abstracted as follows:

(1) The three surveys of the Ice-Patrol Area in the vicinity of the Grand Banks, resulting in as many current-maps, have been described.

(2) The accuracy of salinity-measurements made with the salinity-bridge has been discussed with respect to the use of substandard sea-water and its storage for periods of two to three months.

(3) On the basis of repeated occupations of three different sections in the Grand Banks Region, the seasonal variation in volume of flow, mean temperature, and minimum observed temperature of the Labrador Current during 1941 has been compared with other variations found during the previous seven ice-seasons. The significance of values of minimum observed temperatures has been examined by means of detailed temperature-profiles based on bathythermograph observations made at intervals of about one mile.

(4) The temperature-salinity correlations found in 1941 for the three types of water found in the Ice-Patrol Area have been presented graphically and compared with the eight-year mean 1934-41. Certain long-range trends at various levels have been pointed out and attention called to the importance of corresponding trends in density.

(5) Fluctuations in the boundary between Atlantic-Current water and mixed water or Labrador-Current water during 1941 have been compared with fluctuations during the eight-year period 1934-41. Causes of these fluctuations associated with the North-Atlantic eddy have been separated from the resultant fluctuations and apparent correlations found with fluctuations in the difference in sea-level Bermuda to Charleston. Associated time-lags between different points in the system give promise of the possibility of forecasting that part of the boundary-fluctuation arising from causes connected with the Gulf Stream System. The prediction of fluctuations of the boundary itself still involves an empirical term in connection with the variations in the Labrador Current. Until this term can be adequately explained physically and quantitatively verified the forecast-formula must be regarded as unsafe for extended extrapolation.

(6) The detailed dynamic topography in the immediate vicinity of an iceberg has been shown and an attempt has been made to eliminate tidal effects directly from dynamic heights with the interesting result that in this particular case the current-velocities are considerably modified but the current-pattern is but little changed.

Because of existing war conditions and disruption of normal maritime commerce and practices in the North Atlantic the International Service of Ice Observation and Ice Patrol has been suspended. Because of these same conditions the present oceanographic activities of the Coast Guard are not a proper subject for public discussion at this time.

U. S. Coast Guard,
Washington, D. C.

OCEANOGRAPHIC ACTIVITIES OF THE UNITED STATES COAST AND GEODETIC SURVEY

L. O. Colbert

The oceanographic activities of the United States Coast and Geodetic Survey were somewhat curtailed during the past year due to the fact that survey-units which in previous years had included oceanographic observations in their regular offshore surveying-operations were assigned

to surveys of a different character. In view of the confidential nature of these assignments, it is considered advisable at this time to omit all references to localities of work. At a later date when this information can be made available, this report will be amended for continuity of the record in the Union. Those survey-ships which did continue offshore surveys in the Gulf of Mexico and in Alaska made observations as usual of temperature and salinity to determine the velocity of sound in sea water in each area in connection with echo-sounding corrections and with radio-acoustic ranging for position-determination.

For the first time in the last ten years, when bound to and from the working grounds, our survey-ships did not run sounding lines across the Gulf of Alaska.

During the regular survey-operations, the ship Hydrographer collected bottom-specimens at the special request of the Department of Geology of the University of Florida.

Two new ships, the Explorer and the E. Lester Jones, were added to our survey-fleet last year. This year five more will be added, four of which, the Pathfinder, Patton, Hilgard, and Wainwright, are newly constructed under well-designed plans for their particular assignments. The Pathfinder is 200 feet in length, powered by steam-turbine. The Patton is 88 feet in length, with twin screws and Diesel engines. The Hilgard and Wainwright are large launches planned and equipped for wire-dragging. A former 100-foot yacht was purchased, altered, and outfitted for surveys in the inland waters along the East Coast. This ship has been renamed the Cowie in honor of the late Commander GEORGE D. COWIE, Coast and Geodetic Survey, killed in Manila on December 24, 1941, by a bomb from a Japanese war plane.

In the field of tides, the Coast and Geodetic Survey's system of tide-stations was continued in operation with considerable expansion resulting from war activities and cooperative projects with other countries. Tide-gage installations are now in operation in 98 different localities on an annual basis and the records from these stations are meeting the constantly developing need for comprehensive tide-data.

In cooperation with the United States Engineer Office at Portland, Oregon, a special tidal survey is now in progress on the Columbia River. There are 20 stations in operation between Bonneville Dam and the sea.

The Coast and Geodetic Survey has continued its participation in the program of the State Department of cooperation with the other American Republics through a project for the measurement of tides. Fourteen tide-stations along the coasts of Central and South America have been established from the Gulf of California to the Strait of Magellan. The observations will furnish basic data for the prediction of tides as well as for engineering projects and geophysical studies. As an immediate result of this activity, daily predictions of the tide for the following ports are included in the "Tide tables" of 1943: Salina Cruz, Mexico; La Union, El Salvador; Puntarenas, Costa Rica; Buenaventura, Colombia; Guayaquil, Ecuador; Mararani, Peru. Among the new stations in these tables will be predictions for Darwin, Australia.

It may be of interest to note here that the Bureau has recently published a glossary of tide- and current-terms.

Current-observations were made in tidal waterways by hydrographic parties in connection with their activities. A series of current-observations which were in progress at Frying Pan Shoals and Five Fathom Bank Lightships were interrupted by the removal of these lightships from their stations on account of enemy submarine activities, but a year of continuous hourly observations of the velocity and direction of the current was completed at Portland Lightship. These observations have been made through the cooperation of the United States Coast Guard.

Development work has continued on a radio current-meter which was designed season before last on the ship Explorer in Alaska. Six of these radio current-meters have been manufactured and are now being used and improved by Lieut. Comdr. E. B. ROBERTS on a current-survey by the tender E. Lester Jones.

U. S. Coast and Geodetic Survey,
Washington, D. C.

RESEARCH WITHIN PHYSICAL OCEANOGRAPHY AND SUBMARINE GEOLOGY AT THE SCRIPPS INSTITUTION OF OCEANOGRAPHY DURING APRIL 1941 TO APRIL 1942

H. U. Sverdrup and Staff

(Contribution from the Scripps Institution of Oceanography, New Series, No. 175)

Again emphasis will be placed on the activities in the fields of physical and chemical oceanography and submarine geology, although researches within the biological sciences play a prominent part at the Scripps Institution of Oceanography. The compilation and discussion of field-data and the studies in the laboratory were greatly facilitated until the end of December 1941 by assistance obtained from the Work Projects Administration Project No. 65-1-07-2317.

Within physical oceanography and submarine geology the field- and research-work have been greatly influenced by the war. Since July 1, 1941, the E. W. Scripps has been at the disposal of a University of California Defense Research Project, and several staff-members have been attached to that project.

The six cruises which were planned for the spring of 1941 in cooperation with the United States Fish and Wildlife Service were completed, however, and showed the same general development of the currents as described in the report of 1939, but with different details. The data from these cruises have been partly worked up under the supervision of Messrs. C. E. LA FOND and R. B. TIBBY.

W. C. JACOBS completed an examination of the evaporation from the oceans and the exchange of heat between the ocean and the atmosphere, making extensive use of the data contained in the Atlas of Climatic Charts of the Oceans, published by the United States Weather Bureau in 1938.

G. F. McEWEN has continued the special study of the Colorado River runoff, referred to in the report of 1940-41. In order to advance this work a conference was held at the Scripps Institution on September 5 and 6, 1941, which was attended by representatives of the Bureau of Power and Light of the City of Los Angeles, Professor A. E. DOUGLASS of the Laboratory of Tree Ring Research, University of Arizona, and by representatives of the University of California.

McEWEN has also made progress in dealing with the problem of the horizontal dispersion of material, for example, plankton or fish eggs from an initial source, circular in form and of any given radius. This problem arose in fishery research. Although it has not proved possible exactly to solve this problem--a generalization of the point-source problem whose solution is well known--three different general solutions have been worked out which furnish results approximating closely to the true result.

A generalization has been worked out of the problem of sedimentation from a line-surface source at shore, assuming a constant settling rate and horizontal and vertical diffusion having different values of the diffusion-coefficient. Two general solutions have been worked out for the general case of a continuous-line source not restricted as before to the steady state. This is of special interest to geologists. The solutions found are close approximations.

Conferences have been carried on with Dr. SETTE of the United States Fish and Wildlife Service on statistical aspects of fishery problems, and with biologists at the Scripps Institution on the application of statistical theory to their work.

The statistical theory of the precipitation-ratio used in Dr. GORCZYNSKI'S investigations of climate has been extended and generalized to cover other statistical problems of the maximum and minimum values of a variable having different frequency-distributions.

The climatological investigation by GORCZYNSKI and McEWEN, described at some length in the report of 1940-41, has continued. The main effort in this field has been devoted to preparing the manuscript of the book, "California's climate compared with those of other sunny lands."

Daily observations of temperature, salinity, and weather have been obtained from six shore-stations, including the station at the end of the Scripps Institution Pier. Supplementary observations from United States Lighthouse tenders and tuna clipper-ships have been collected. At the Scripps Institution continuous barograph and pyrheliometer-records, as well as daily observations of humidity and precipitation, have been made.

Because, during most of the time since July, 1941, clerical help was greatly reduced and was mainly occupied in preparing the manuscript for the book on climate, special attention was given to certain mathematical problems arising in the fields of climatology and oceanography in order to provide the necessary foundation for numerical applications to be carried out later. Encouraging progress has been made in this undertaking.

Under the direction of E. G. MOBERG two investigations of importance in the physical chemistry of sea water were initiated. One of these, carried out by JAMES C. HINDMAN, deals with the much-investigated but still unsolved problem of the solubility of calcium carbonate in sea water, and is a corollary of the work of JOHN LYMAN on the buffer-mechanism, particularly on the dissociation constants of carbonic and boric acids, in sea water and which was reported upon in 1941. Mr. HINDMAN obtains the data for the calculation of the solubility-product constants of the carbonates of calcium and other alkaline earths by titration of their chlorides or nitrates with sodium carbonate by methods and under conditions capable of yielding results of a high degree of accuracy. By this procedure certain peculiarities in the behavior of calcium carbonate have been observed. These will probably explain the divergent views regarding the relative concentration of calcium carbonate in sea water that have been published.

The other investigation was undertaken with a view of finding a method for determining the chlorinity of sea water more accurately than is possible with the standard KNUDSEN method. Such a method was especially needed for evaluating reference (standard) sea-water samples which are no longer obtainable from the usual source. A potentiometric titration-method was adopted, and to serve as a titration end-point indicator a vacuum-tube voltmeter of high sensitivity and wide range of application was designed and constructed by L. J. ANDERSON and J. C. HINDMAN. A paper describing the construction and uses of this voltmeter has been prepared.

A novel feature of this potentiometric titration-method is the introduction of the reversible silver-silver chloride electrode as the indicating electrode and an electrode of platinum immersed in KNO_3 and sealed in glass as the reference. Contact with the solution is made through an asbestos filter. Using these electrodes together with the voltmeter above mentioned and a weight-technique with mechanical agitation, a precision in the determination of chloride of ± 0.005 per mille has been obtained. A comparison of Copenhagen standard sea-water with a primary sodium-chloride standard has been made. The results obtained show a difference of only 0.002 per mille between these standards. The results indicate that this method and standard sodium chloride have much to recommend them. The time involved in the titration is far less than in the VOLHARD procedure and the accuracy and precision are greater. Comparisons were also made with the colorimetric MOHR (or KNUDSEN) method using similar technique. Excellent agreement was obtained indicating that under proper conditions the MOHR titration is capable of high precision.

The work of the Sediments Division has been greatly reduced because R. R. REVELLE, in charge of the Division, was called to active duty in the Navy on July 10, 1941. Routine analyses were carried out by L. J. ANDERSON with the help of a Work Projects Administration assistant until the discontinuance of the project at the Institution in December. About 250 individual samples of marine sediments were analyzed for particle-size distribution and for water-content during the nine-month period. The water-content analyses were made first on the basis of the weight-loss on drying, and then on the basis of the chloride content of the sample. Analyses for chloride were made on all samples by means of a conductometric method developed in the Division. This method eliminates the necessity of leaching the chloride out of the mud before analysis because the presence of mud-particles does not interfere with the electrically-determined end-point of the silver-nitrate titration. About 20 samples were analyzed for nitrogen and sulfur in connection with investigations undertaken by REVELLE and RITTENBERG on the sulfur cycle in marine sediments. The procedure used for determining calcium carbonate in the sediments was improved and work was started on the development of another one based on a different principle.

Intermittently, during the entire year a conductometric method for determining sulfate in sea water and marine mud has been improved. The main substance that interferes is calcium, which coprecipitates with barium sulfate in the titration. Convenient ways of removing the calcium are being investigated at present.

Other investigations by L. J. ANDERSON on potentiometric titration were described above when reporting on work in the division of chemistry.

F. P. SHEPARD has prepared a series of charts of the Gulf of California and adjacent territory, incorporating in them the 25,000 soundings of the E. W. Scripps Expedition of 1940 to the

Gulf and the 3,000 soundings of the Expedition of 1939. These charts have been contoured and are now ready for publication. The report on the submarine topography of the Gulf of California has also been written. This report contains a discussion of the numerous fault-scarps discovered on the floor of the Gulf, with suggestions of the history of earth-movements which these scarps indicate. Also the submarine canyons of the Gulf are considered at some length. The localization of these canyons in the more humid areas is considered and the relation between these canyons and the diastrophic history is discussed.

As far as possible, work has continued on the study of beach-erosion and long-shore drift of sand in La Jolla Cove. Currents were observed daily at 14 stations in the Bay during the past summer. Analyses of the wave-records obtained daily at the Institution Pier have been made with the cooperation of E. C. LA FOND and W. F. WOHNUS and show that the waves have a period which averages about 9.2 seconds. Storm-waves in general have shorter periods and the small wind-waves in summer also have short periods. Erosion of the beach and foreshore show direct relation to the character of the waves. Direct relations between quantity of mica on the beach and quantity of heavy black sands to the size of the waves were also established, the mica decreasing and the black sand increasing with increase in size of waves. Also, mica was found to occupy the troughs of ripples on the beach and black sand on the seaward slope of the ripple-marks. More evidence was obtained showing the importance of the location of rip-currents to beach-erosion during the stormy season.

Scripps Institution of Oceanography,
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RELATED PROBLEMS IN SHORE-PROCESSES AND OCEANOGRAPHY

Martin A. Mason

Shoreline-processes have become increasingly important in the life of the nation since the advent of good highways and excellent transportation facilities has brought the shore within a few hours' trip of populous centers. Shorefront development has been rapid and land values have reached large figures; for example, it is said that the assessed valuation of the shorefront of Absecon Island, including Atlantic City, is in excess of $300,000,000. Correspondingly with increased valuations public interest in the protection of shorefront property has increased. The Congress, recognizing such interest, as well as the value to the country at large of shoreline protection, created the Beach Erosion Board under the War Department in 1930. The authority and duties of this Board, composed of four officers of the Corps of Engineers and three civilian members, all familiar with shoreline-problems, were amplified and extended in 1936.

Its function is described as ". . . to cause investigations and studies to be made in cooperation with the appropriate agencies of various States on the Atlantic, Pacific, and Gulf coasts and on the Great Lakes, and the territories, with a view to devising effective means of preventing erosion of the shores of coastal and lake waters by waves and currents . . ." and ". . . to make investigations with a view to determining the most suitable methods of beach-protection and restoration of beaches in different localities; to advise States, counties, municipalities, or individuals of the appropriate locations for recreational facilities; and to publish from time to time such useful data and information concerning the protection of beaches as the Board may deem to be of value to the people of the United States . . ." The Board's activities are defined to extend to the Atlantic, Pacific and Gulf coasts, the Great Lakes, and the territories. In so far as is known, the Beach Erosion Board is the only organization of its nature now functioning in the world.

Every effort is being made to place the art of shore-protection and the study of shoreline-processes on a rational scientific basis. The problems involved are probably familiar to some of you and you realize their complexity and intractable nature. Many observers believe the problems to be too complex to admit of solution; but it may be said that we do not know enough about the problems as yet to make even this statement with certainty. It is in the hope of enlisting the cooperation and aid of oceanographers and oceanographic-study agencies in the solution of problems common to shoreline-processes and oceanography that this paper is being presented.

Most of the studies made in physical oceanography have a more or less direct application to shoreline-processes. In fact it might be pointed out that oceanographers are concerned principally with oceanic phenomena in regions removed from the coastline, while the investigator of shoreline-processes is concerned with the same phenomena as they affect the coastline.

In this rather general discussion of problems only the broad questions common to both fields will be mentioned, with some indication as to the information it is desirable to obtain. Doubtless a moment's thought will bring to mind many ramifications of each of the general problems to be described, but no attempt will be made to cover such questions in detail.

Probably the most important single problem confronting both the oceanographer and the student of shoreline-processes is the question of the interaction between the sea and the atmosphere. In its broadest interpretation we should be involved in the whole problem of oceanic circulation; however, we shall limit our consideration to only the interface between sea and atmosphere. Obviously a related question, which is similar in some details, is the action at the sea-land zone of contact represented by the ocean floor or the beach.

Shoreline investigators are primarily concerned with the surface-effects of sea-air interaction, that is, surface-waves, and wind- or wave-induced currents, in the area contiguous to the coastline. Special attention must be paid therefore to the problems of wind-stress on the sea-surface. It is necessary to consider not only offshore winds but also local winds. Present thought among shoreline investigators is that a study of offshore winds and their effects is necessary to a determination of the predominant direction of approach and maximum characteristics of the waves reaching the coast. It is believed that, in general, the most destructive waves are generated many miles offshore by wind- or storm-action and travel shoreward. During their travel they may be subjected to the influence of many variable winds other than the generating wind, of other wave-systems, and particularly as they approach the shore, of local winds. Local winds are believed to have an appreciable effect on the magnitude and direction of approach of offshore waves, entirely aside from their action in generating waves.

The situation is admittedly difficult and perhaps the only successful result yet obtained is the empirical relation established by the French for the forecast of swells on the North African Coast. It is interesting to note that a similar situation exists on our Southern California Coast, where the coincidence of offshore swells with high tides frequently causes serious property damage. The possibility that these swells are related to the passage of a depression over the Polynesian Islands area is not fantastic.

For lack of better methods, the Beach Erosion Board has attempted in the past to obtain necessary information from a study of observed effects on the shoreline, coupled with short-term records of local observations of wind and wave. What is needed, however, is a long-term statistical record of wave- and wind-characteristics at the locality involved; or lacking that, similar records for any locality with a method of modifying the records to apply to the area under study.

The movement of material on the ocean bottom bordering the shoreline is a second subject of great importance in shoreline protection. It is desirable to know how wave- and current-action affect the stability of the shore; how and under what conditions beach-material may be transported; whether beach-material may be carried offshore to great depths or onshore from considerable depths. One of the items which must be determined before any protective works, such as groins or jetties, may be designed or built is the quantity of sand in movement along the shore and the seaward extent of the area in which it moves. Some tests have indicated that the major portion of the material in movement is confined to the zone shoreward of the wave plunge point; other evidence, however, shows appreciable movement of bottom material in depths of as much as 50 feet. The need for accurate instruments and techniques for the determination of the amount of bottom or beach-material in movement is great.

Closely related to the movement of material is the problem of the measurement of currents near the shore. Any complete solution of the problem of wave-action on the shoreline must include information on the relation between movement of material, material-size, wave-characteristics, and alongshore currents.

Another of the related problems being discussed is the question of hydrographic surveys. Trends in the behavior of shoreline-areas are studied by means of hydrographic surveys locating the shoreline, either low or high water, and the offshore contours out to about the 48-foot depth as a maximum, although where unusual bottom topography exists the limits may be extended into deep water. This would be the case for example where submarine canyons approach closely to shore. Surveys used in such comparisons must be as accurate as possible, particularly when studying areas characterized by flat slopes. It will be recognized that an error permissible in sounding great depths may not be allowed in comparative surveys seeking to determine short-period changes of shallow areas. While not a serious deficiency, the need for more accurate and less expensive methods of hydrographic surveying in depths less than about 50 feet is evident.

Lastly, the engineer concerned with shoreline protection is deeply interested in tidal and mean sea-level variations. His problem is three-dimensional in that he must design protective works that extend along the shore sufficiently to save a certain area from harm, that project far enough seaward to trap sand in movement or protect from denudation what beach exists, and that cover a sufficient vertical range to operate efficiently when the elevation of the sea-land-surface intersection is shifted by a change of water-level. Measured and predicted tidal and mean sea-level variations are indispensable here. It may be noted that the top elevation of breakwaters, bulkheads, seawalls, and groins is largely determined by considerations of tidal levels and maximum wave- and wind-action.

These then are some of the related problems in the fields of shoreline study and oceanography. Progress has been made toward the solution of many of the problems, while the solution of others seems at the moment to present great difficulty. It is believed, however, that none of the questions are insoluble, provided the correlated effort of all agencies or individuals working in related fields be directed in a coordinated attack.

War Department,
Office of the Chief of Engineers,
Beach Erosion Board,
Washington, D. C.

UNITED STATES NAVY CONTRIBUTION TO THE OCEANOGRAPHY OF THE CARIBBEAN SEA WITH SPECIAL REFERENCE TO THE THRESHOLDS BETWEEN BASINS

T. H. Whitcroft

The Caribbean Sea is the "Mare Nostrum" of the Western Hemisphere, and it can be safely said that today we have more data on this large body of water than there is on the original "Mare Nostrum". The Hydrographic Office of the United States Navy has contributed largely to this knowledge, in tidal studies, dynamic soundings, gravity-measurements, currents, and bathymetry. To cover all these phases would occupy most of the afternoon, so I shall restrict my remarks to bathymetry, and especially to the thresholds between the various basins in this area.

Since the development of sonic sounding-devices, all United States Naval vessels have been taking soundings when voyaging from port to port. At times, some of these ships have been sent far off their regular routes to obtain depth information in heretofore unsounded areas.

Since 1929, oceanic sounding data obtained by Naval vessels have increased in volume each year so that today we can delineate the 500-fathom curves on a scale of 1:150,000 with reasonable accuracy over the greater part of the Caribbean Sea and the Gulf of Mexico. During this period, there have been reported by ships and subsequently plotted in the Hydrographic Office over 50,000 nautical miles of soundings in this area alone. The United States Naval surveys have added many more miles not considered in the above amount.

This mass of data is from navigational lines and gives us a picture of the form and shapes of the various basins, and also a very fine reconnaissance of special areas that, for scientific purposes, should be developed with a controlled survey. The most important of these special areas are the thresholds between the various basins, and it is on these that I will report the information we have to date. In that it is the function of my work to secure and present data on oceanic soundings for the use of scientists and navigators, I will welcome brief inquiries, item by item, as I present the data we have on each of these areas.

The chartlet of Figure 1 presents the basins of the area and the thresholds (heavy lines) between them. Beginning with the Mexican Basin, and working toward the North Atlantic Ocean, the outlets are Florida Strait and the Yucatan Channel. The well-developed Florida Strait, which is very shallow, establishes the control-threshold in the Yucatan Channel. For the purpose of this article, the Yucatan Basin and the Cayman Trough can be considered as one body of water, as their separation by the Cayman Ridge is over 1,500 fathoms in places. The east end of the Cayman Trough is separated from the Hispaniola Trough (name suggested) in the Windward Passage by a depth of 915 fathoms; and it is separated from the Colombian Basin by the Navassa Swell, on which are depths of 843 or possibly 1,000 fathoms. The Colombian Basin is separated from the Venezuelan Basin by the Beta Ridge at the southern extremity of which are depths of over 2,200 fathoms. From the Venezuelan Basin to the Atlantic, the threshold is about 1,067 fathoms in the Anegada Trough. The Aves Swell with a threshold of 870 fathoms at the northern end, separates the

Venezuelan Basin from the Granada Trough. The Granada Trough makes out into the North Atlantic through the Martinique and St. Lucian channels, with depths of 574 and 591 fathoms, respectively.

Figure 2 is a schematic diagram showing all thresholds that are deeper than 500 fathoms. Using the 1,000-fathom curve as a criterion, we can eliminate several areas as not being critical. There is a continuity of the 1,000-fathom curve from the Atlantic through the Anegada Passage to Navassa and from Navassa into the Gulf of Mexico through the Yucatan Channel. The Cayman Ridge

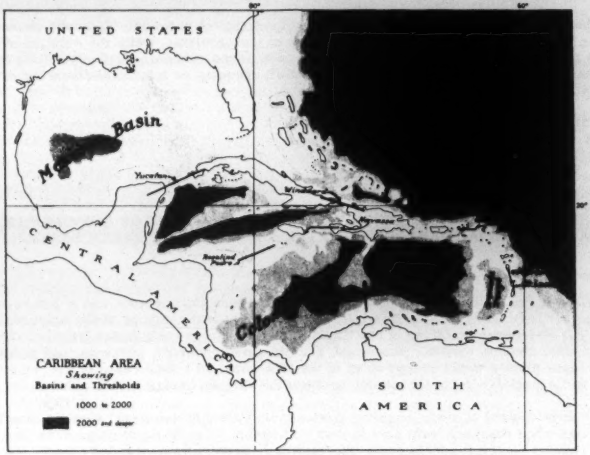

Fig. 1--Caribbean Area showing basins and thresholds

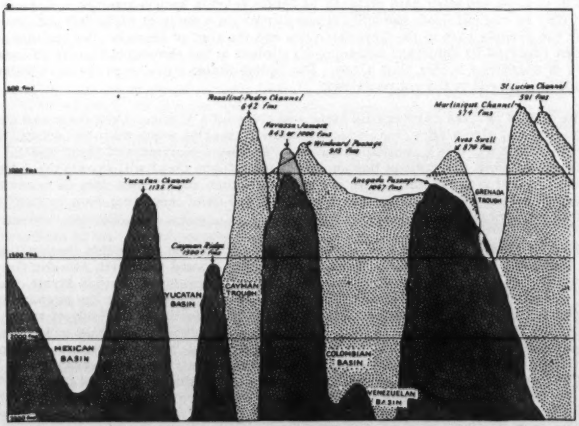

Fig. 2--Diagram of thresholds and basins

and the Beta Ridge are too deep to be considered in this presentation. The Rosalind-Pedro Channel is the deepest of the many channels through the shoalings between Cape Gracias a Dios and Jamaica, and is the least developed, although such soundings as we have show a depth of between 600 and 700 fathoms. The 591-fathom threshold at St. Lucian Channel and the 574-fathom threshold to the north in Martinique Channel can be considered as being nearly the true threshold-

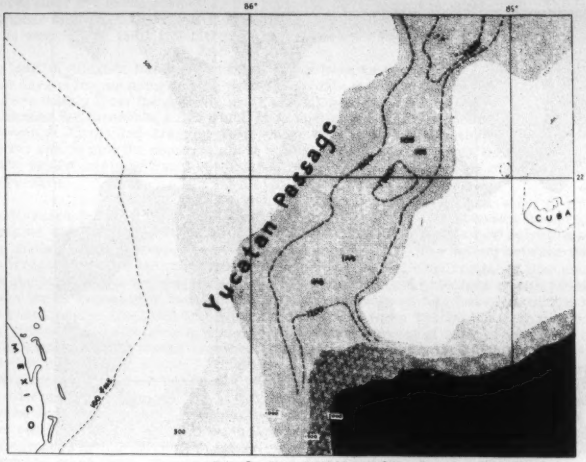

Fig. 3--Yucatan Channel

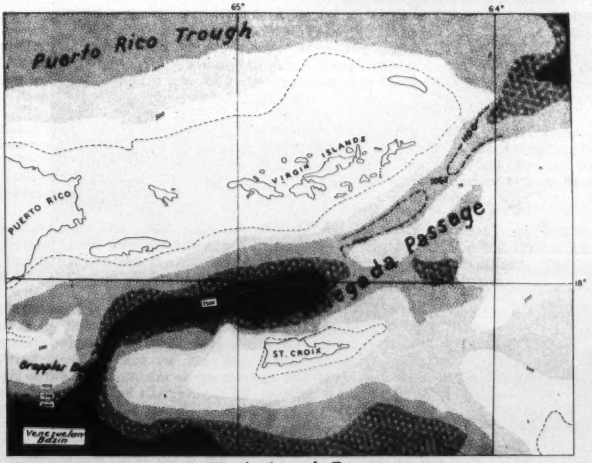

Fig. 4--Anegada Passage

depths, although these channels have not been adequately developed.

Of the remaining thresholds, two, Anegada and Yucatan channels, have a positive continuity of the 1,000-fathom curve, and one, Navassa Passage, has a probable connection. The fourth, Windward Passage, does not have a 1,000-fathom connection, but since new data have been added re-

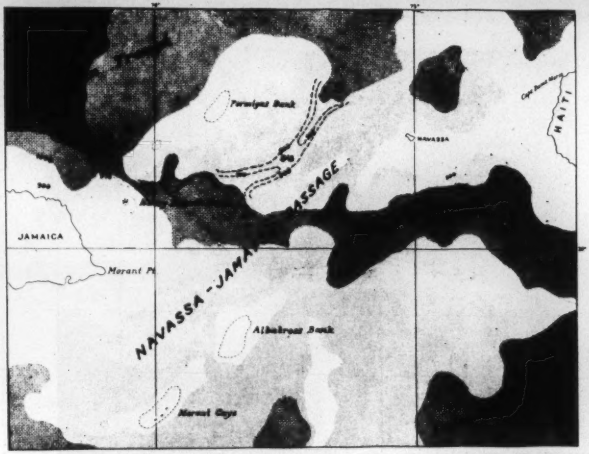

Fig. 5--Navassa-Jamaica Passage

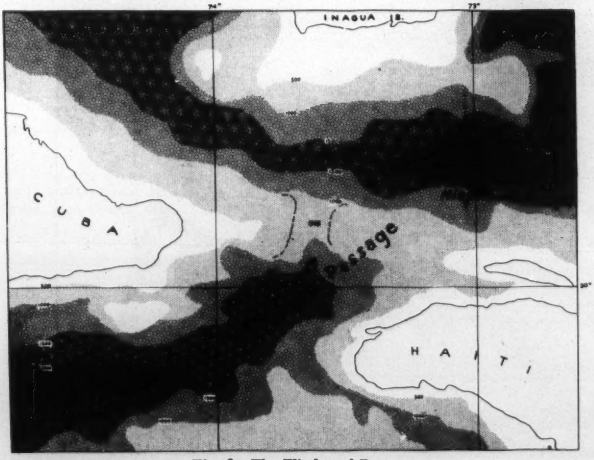

Fig. 6--The Windward Passage

cently, the Windward Passage is presented for what interest it may have.

In the Yucatan Channel as in Figure 3, the 1,100-fathom curve is continuous, but the 1,200-fathom curve extends only a short distance in the direction of the trough of the Channel and re-curves into the two basins. There is verification by many soundings of the 1,200-fathom hole that appears due west of Cuba. This hole and the channel to the north of it is rather well developed by navigational lines but in the channel to the south the development is inadequate. The few soundings that do appear are well placed, and it is reasonable to assume that all the southern part of the Channel is deeper than the 1,135-fathom threshold at the northern portion.

The fault in Anegada Passage (see Fig. 4) has been known to exist for a long time, and although we have many soundings in the area, more data would be welcomed. The 1,100-fathom curve enters deeply from the Atlantic and Caribbean sides, and turns back. A shoaling to 1,067 fathoms makes the threshold-depth which is at a point opposite the Barracuda Bank. There is an area between St. Croix and Grapples Bank where very little investigation has been done. All bathymetric charts pull the contours above 2,500 fathoms into St. Croix Basin. There is a chance that lesser depths might be found in this area, which would make a ridge closing off some of the deeper contours.

The Navassa-Jamaica Passage Area (Fig. 5) is where most of the sounding lines reported to the Hydrographic Office have been run. From this mass of information, a new selection of soundings has been made, and our charts have been revised accordingly. The bottom between these islands is more irregular than in the other area of the Caribbean, and requires more than usual data to delineate the curves with any degree of accuracy. A prominent wide deep trough extends from the Colombian Basin westward to the Cayman Trough. There is no conclusive proof that there is a positive connection of the 1,000-fathom curve into the Cayman Trough but it is very possible. The recently plotted soundings present a more detailed development of most of the length of this feature. The east end of the trough is not very well developed but from the information we do have, we know that the depths are over 1,000 fathoms. The 1,500-fathom spots south of Navassa Island which have appeared on past issues of Hydrographic Office charts have been very well developed and are all connected into one large area. This, we may find, when a more detailed survey is made, to be connected with the 1,500-fathom water of the Colombian Basin. The west end of this trough is really undeveloped. Formigas Bank was surveyed before sonic apparatus was perfected and only extended to the 100-fathom curve. The 33-fathom spot, Henry Holmes Bank, was developed about the same time. Between these two banks, there are over eight miles of undeveloped water.

There are soundings of over 975 fathoms three miles north of the 33-fathom soundings and no other soundings until we reach the south end of Formigas Bank. In this immediate vicinity, soundings fall off as much as 750 fathoms in a distance of less than two miles. Such steep slopes could very easily exist through this area of no information, thus connecting the Colombian Basin with Cayman Trough by a trench of over 1,000 fathoms.

On older issues of Hydrographic Office charts of this area, a 1,002-fathom sounding existed near where we now have the 843. It was thought that a tongue of the 1,000-fathom curve extended to this 1,002-fathom depth and was a lead to the threshold across this rise. Present soundings show an 800-fathom trench through this rise, with the 900-fathom contours turning back at an 843-fathom threshold.

It is interesting to note the alignment of the shoalings south and west from Navassa Island and the parallelism of the shoals south and west from Formigas Bank. The 800-fathom trench is also parallel to this system and is about midway between the two lines of shoalings. The transverse trench of 1,100 fathoms cuts through both of these parallel lines of shoalings.

The Windward Passage (see Fig. 6) on the Cuban side was developed by a controlled survey to the end of the 500-fathom shoaling. Beyond that, there are but few lines reported by ships. On the Hispaniola Island side, there were many lines reported by ships cruising along the North Coast of Haiti; therefore, we have the least data in the center. But the data we do have precludes the connection of the 1,000-fathom curve through this ridge. The 900-fathom contour re-curves on each side of the ridge and our present information leads us to believe that the threshold on this ridge is 915 fathoms.

It is interesting to know that the 2,000-fathom trough north of Hispaniola is not continuous with the 2,000-fathom curve out of the Puerto Rican Trough, as has been shown on bathymetric charts of this area, but is cut off by a 495-fathom bank between Silver Bank and Cape Viejo Frances.

At this time when all effort is diverted toward the successful conclusion of this war, little new data can be expected in oceanic soundings. After that conclusion has been reached, a great volume of data can be expected. As many as 150,000 miles of sounding lines a year would be a very conservative estimate. These data will be in long navigational lines of soundings over the oceans of the world. These special areas that I have outlined here so briefly will be added to with no real plan, so in order to secure conclusive data special expeditions will have to be organized. This will offer an opportunity for many small projects which scientific bodies could accomplish in conjunction with other studies. The Hydrographer always welcomes data from any source, and especially values data of the quality usually received from scientific expeditions.

U. S. Hydrographic Office,
Washington, D. C.

SOME OBSERVATIONS ON THE PERUVIAN COASTAL CURRENT

Milton J. Lobell

One result of our recently expanding cooperative activities with the other American Republics was a request by the Government of Peru for a survey of the marine resources of that Republic. This survey was to be conducted by the Fish and Wildlife Service of the United States Department of the Interior.

Headed by REGINALD H. FIEDLER, Chief of the Service's Division of Fishery Industries, a Mission was selected for the work. I was detailed to conduct the field-work relative to exploratory fishing, fishing-gear studies, and the biological and oceanographical phases affecting the supply of commercial fish. To enable this portion of the study to be carried out, the 80-foot purse-seine fishing-boat, Pacific Queen, was chartered and equipped with the necessary fishing-apparatus and oceanographic equipment.

We sailed from San Pedro, California, January 26, arriving in Callao February 13. In order to avoid bad weather and save as much time as possible the trip was made offshore. Our only stop on the 17-day voyage was for four hours at Charles Island of the Galapagos Group to transfer oil from our deck-load of drums to our fuel tanks.

The strange untropical qualities of the coastal waters of Peru have been a subject of discussion since the earliest explorations. Numerous theories have been advanced to explain the coldness of the water--some of these are reasonable, others are not.

HUMBOLDT'S observations in 1802 led to a conception of a cold coastal current of Antarctic origin, for he found that the water was cooler than the air and that these cold waters disappeared rapidly in proceeding offshore. His theory was strengthened by the observations of a northward-flowing current.

Workers up to 1837, including three French expeditions, generally followed HUMBOLDT'S views.

In 1837, however, BOUGAINVILLE pointed out that the surface-waters off Valparaiso, Chile, were very little lower in temperature than those off Callao, Peru. He was followed by DE TESSAN, in 1844, who first suggested that the low surface-temperatures were due to the upwelling of subsurface layers of water. MAURY, also in 1844, DINKLAGE in 1874, and WITTE in 1880 presented further data in support of the theory of upwelling.

Since 1900 a number of workers have published articles on the phenomenon of the Humboldt Current. In general these investigators have strengthened the upwelling concept, and with their use of modern oceanographic equipment a great amount of evidence has been produced.

As a result of this evidence we can synthesize a picture of the normal oceanographic conditions in the area. The essential points are:

(1) Cold water from 14° to 16° C is found immediately inshore.
(2) This water is dark green in color except where modified by local conditions such as contamination by river-water or blossoming of plankton.
(3) These waters support tremendous concentrations of plankton and, as a result of this, myriads of fish and birds.

(4) A northward current is present in certain areas and is lacking in others. There is a greater velocity inshore than offshore.
(5) The surface is less saline inshore than offshore.
(6) In proceeding offshore surface-temperatures rise--at 20 miles offshore they may be 17° to 18°, at 50 miles 20° to 21°, at 100 miles 23° to 25°
(7) In proceeding offshore, the color of the water changes from green to murky blue and finally to a clear aquamarine.
(8) Several investigators, including GUNTHER, present evidence to show that wedges of warm water are present and that swirls and eddies occur more or less regularly.
(9) The above conditions occur about as far north as Punta Aguja regularly and occasionally to Cabo Blanco.
(10) Very little variation in temperature occurs from day to day, month to month, and year to year along the coast from about Valparaiso to about Punta Aguja.

In contrast to these more or less general conditions normally present, there is mention made of variations in the oceanography. These observations have been reported by a number of investigators and the general picture is as follows:

(1) Local fishermen and some local writers claim that the Humboldt Current swings offshore in the north of Peru. A current of hot water of low salinity from the Equatorial Counter-Current then is reported to flow southward and this affects markedly the inshore water-conditions and the coast. They know this current as El Nino (the child) because it appears shortly after Christmas Time.
(2) The existence of El Nino is confirmed by numerous workers. SCHOTT (1931) says it is caused by northerly winds.
(3) While El Nino has been reported as far south as Pisco this is doubtful, and its usual southward extension is little south of Salaverry.
(4) El Nino is most prevalent during January to March.
(5) Torrential rains, thunder-storms, above-average air-temperatures and humidity occur.
(6) Birds desert the Guano Islands, thousands die, anchovy-schools vanish, and hammerhead-sharks and manta-rays appear.
(7) A condition known as aguaje often appears during or after El Nino and causes death of myriads of fish which are cast up on beaches and remaining in the water cause discoloration of paintwork on ships.

The conditions which we observed in the Peruvian Region from February to June, 1941, varied significantly from any previously recorded.

SCHWEIGGER reported that the summer of 1939 was extraordinary because of warm waters immediately inshore. VOGT and others reported a large mortality in the populations of guano birds. For this reason, we were prepared for some variation in the oceanographic conditions but the differences we found were so great that the recurring impression to me, at least, was one of bewilderment, for it was difficult to realize that a portion of the ocean could change so completely.

At the Galapagos, during the trip to Peru, the inhabitants told us that "the sea is sick". They reported unusually heavy rains and poor fishing. Portions of the islands reported to be barren were green with vegetation. Dry stream-beds were flowing bank-full. The unusual conditions in the Galapagos were to be the first of many others observed before our work was done.

From the Galapagos to the islands of Lobos de Afuera, about 50 miles off the coast of Peru, we took surface-temperatures hoping to find some trace of the cold waters reported in this region. We found none--the average temperature of the surface of the sea was 25°C and the lowest we recorded was 22° C, near Lobos de Afuera. During the transit, we had hot, sultry weather with occasional rain squalls, very much different from weather on a previous trip through a part of these same waters, when the air was cool and the sky was overcast.

Coasting about 30 miles offshore southeastward en route to Callao, we continued to take temperatures. We found that while there was some variation, the lowest were not below 21°C. The water was of a murky, deep, indigo-blue color--much like a strong solution of blueing. Even 30 miles offshore, long lines of dead birds littered the surface of the water and, as far as I could determine, all were cormorants or pelicans. We counted many hundreds of them.

During this time the air was warm and sticky; at times a light drizzle came down. During the night a heavy dew settled on the decks and rigging. Over the coast vivid flashes of lightning stabbed the darkness and threw the rugged shore into sharp recurrent silhouettes. The offshore

winds were usually light and seemed to blow more from the south than from the southeast.

On the second day, heading southward, we came closer inshore to take a look at the coast and try some trolling. As we proceeded we saw numbers of hammerhead-sharks. Several times we thought we might be able to harpoon a swordfish or marlin when we saw the twin fins cleave the surface. Each time, however, the fish proved to be a huge manta-ray, and the "twin fins" the ends of the wings curling above the surface. Later we saw these huge sea-beasts top the water again and again, each time falling back with a heavy splash of white water. A mile or so off Salinas Promontory, yellowfin and skipjack-tuna started to strike our jigs, and we saw schools of these fish in all directions. The guano island of Mazorka was practically bare of birds, but this was not true of the sea, for the blue waters about were dotted with dead birds by the score.

It really did not take the conversation with Dr. SCHWEIGGER the next day to convince me that the world of the Peruvian Coast, at least, was upside down.

On shore the effects of the changes were no less noticeable than on the sea. Each day more vivid stories were told of the vast numbers of dying birds. Bathers at the seashore were happy, for the water was warmer than it had been for a long time. Of course, there were dead birds on the beaches but------.

In the foothills of the Andes thunder-storms and cloudbursts destroyed bridges and roads. Lima went without lights for more than a week when transmission-lines were destroyed. The people discussed the flashes of lightning which they were able to see from their windows in the city. This phenomenon is rarely seen in Lima. The barren foothills and the deserts of northern Peru blossomed and green vegetation covered the ground. Fishermen complained that their means of livelihood had all but disappeared. Floods in the mountains brought warnings not to drink the local water because of the fear of contamination of the water-supply from the sewage-carrying irrigation-ditches and drainage-ditches.

Our fishing efforts during the first part of the work of the Mission were rather fruitless. The hauls with the otter trawl were without exception water-hauls--our trawl-lines came up bare. The enormous schools of anchovies did not show up, and to this some people ascribed the heavy mortality in the guano-bird population. The only kind of fishing we were able to carry on with success was that by trolling, and we caught large numbers of yellowfin and striped tuna and dolphins. On a number of trips made during the night, to our surprise we found tremendous concentrations of anchovies. With the coming of daylight, however, these myriads of fishes disappeared, and during the days no such schools were to be seen.

During the month of March we made a long trip southward, going down right along the coast. Here surface-temperatures inshore averaged about 25° C. One spot of water of 19°C was found at Atico. We saw mantas, hammerheads, tunas, dolphins, and flying-fish all within a mile or so of shore. The water was a deep translucent blue for the most part, but within the bays and around the outlying points--as Atico, where we found water of 19°--the color was a murky green. Off Punta Coles, about 40 miles north of the Chilean border, we were surprised to see many blue sharks and mantas.

Our return trip northward was made offshore, starting about 75 miles west of Ilo and proceeding northward to converge with the coast at about Independencia Bay. Offshore we found surface-temperatures ranging up to 26°C. Again we found dolphins, flying-fish, and a few tuna. We passed through large concentrations of Porpita and Ianthina. In the region of Mollendo we crossed a tongue of warm water presumably pushing inshore. This tongue was about 50 miles wide, and the temperatures within it showed a progressive rise and then a decline. Nowhere did we find any evidence of cold water or of the normal northward-flowing current.

In the following months we made trips offshore and to the northward--going out to sea 200 miles and to Puerto Pizarro, the northern port of Peru. At no time did we encounter water of less than 19°C. Invariably the temperatures rose as we proceeded offshore, and at 30 to 40 miles from land they would run 25° to 26°. There was little latitudinal variation offshore, but closer inshore considerable fluctuations could be detected. In the Gulf of Guayaquil, for instance, we found temperatures up to 29°C. Offshore the water was usually clear and blue, but immediately inshore it would be discolored. During this period we continued to take tunas and dolphins and to see mantas, hammerhead-sharks, and flying-fish. We found some evidence of a southward-flowing current from the Gulf of Guayaquil southward almost as far as Salaverry.

In June, however, conditions started to change. From Callao to Salaverry we found water of

19° inshore. From five to ten miles off the coast warmer water was found, and we took very large catches of tuna around Isla San Lorenzo. Sometime during the second week in June, the surface-temperature at San Lorenzo Island dropped almost 4°C. We found water of 16° in the latter part of June from Callao to Supe. During this period the color of the inshore water gradually assumed a green murky color although areas of discoloration to grey were noticed. The immense schools of tuna inshore disappeared completely. No more mantas or hammerheads were observed. Long lines of guanayes were to be seen and schools of anchovies appeared even within Callao Harbor.

We made a trip offshore during the latter part of June, in an attempt to find the warm water and, if possible, tuna. Proceeding offshore, almost due west, we found a gradual increase in the surface-temperatures until at Hormigas de Afuera, about 40 miles off Callao, we found water of 18° to 19° of a transitional type between the inshore green and the offshore ultramarine. And in this area we found tuna.

Heading northward, then, to reach Mazorka Island, we found the temperatures dropped as we came closer to land. About 15 miles southwest of Mazorka Island in water of about 16°.5 C, we found at least 15 dead yellowfin tuna floating in the water. The only reason that I can ascribe for this is the rapid decrease in the temperature.

In July, water of 16° was found inshore from Independencia Bay to Punta Aguja, and water of 17° off Talara. North of Talara and into the Gulf of Guayaquil, the temperatures rose rapidly up to about 20° C, near Zorritos. During the last part of July, the temperatures continued to drop; we found water of 15° between Callao and Huacho, between Chimbote and Salaverry, and off Talara.

In August the temperatures dropped still further, and we found water of 14° near Santa Island and just outside Chimbote Bay. Offshore the temperatures still were warmer than inshore, but the rapid rise detected in the earlier months of the year was not present. At 50 miles from the coast, the average temperature might be in the neighborhood of 20° or 21°, whereas previously it was 25° or 26°

In general then, we may regard the period from February to June as an abnormal time when hot water was found along the entire coast. This hot water was accompanied by mantas, hammerheads, tunas, and flying-fish--all of which are definitely warm-water forms. There was a scarcity of anchovies, bonitos, and bottom-fish. The scarcity of food had a very disastrous effect on the guano birds, and thousands died. The distribution of rainfall and air-temperatures was unusual.

From June on we found that the oceanographic conditions were returning to normal. The hot water and the hot-water forms disappeared in the inshore water. Cold water of a green color replaced the oceanic blue. Anchovies and bonitos appeared in ever-increasing numbers.

After June 15, when we found that we could no longer find tuna inshore, we initiated a series of trips offshore to find the whereabouts of the tuna and the warm water. We found in the Callao Region that we could expect to find tuna about 40 miles offshore in waters from 17° and over--we never saw or caught tuna at temperatures lower than 17°.

As a result of these cruises, we found a very interesting condition suggested previously by GUNTHER, SCHOTT, and by others, that is, the presence of warm-water tongues or wedges. We located such tongues at a number of points along the coast, one each near Mollendo, Paracas Peninsula, Mazorka Island, and off Salaverry. These areas usually appeared to be pushing in from the west or northwest and were from 30 to 50 miles wide. They were found to represent a shoreward extension of warm water of as much as 20 to 30 miles.

We were able on several occasions to cross these tongues and, as an example, let me give the series of temperature-readings obtained in transiting one pushing in toward Cerro Azul.

This trip was made on August 16, leaving from Chincha Island and proceeding more or less northwest. At 933 the surface-temperature at Chincha Island Norte was 15°.4. At 1,100, about 13 miles northwest of Chincha, it was 16°.2. Just before 1,200, the water started to change to a blueish tinge, and at 1,200 the temperature was 17°.2. Just after 1,200, tuna and skipjack started to hit, and the water gradually took on an ultramarine color. At 1,245, the temperature was 17°.8, at 1,315 it was 18°.0--and here the water was definitely blue.

At 1,400 the temperature had dropped to 17°.8. It then dropped rapidly, until at 1,630 it was 16°.0. The last tuna was taken at 1,500 in a temperature between 16°.9 and 17°.0. The water at 16°.0 had shifted back to a greenish color. From 1,630 on, the temperature rose gradually to 1,800 when

it was 16°6, then rapidly to 17°2, when several tuna were again taken. At 1,900 the temperature was 17°4, and at 2,000 it was 18°0.

Unfortunately, as it had become dark, it was impossible to detect the color of the water at this point. This line was continued, however, and it was found that while there was the suggestion of another tongue of warm water pushing in toward Ancon and Callao, the temperatures showed a general rise so that, about 200 miles offshore of Supe, the temperature was about 20°5 C.

At this point the course was changed to almost due north toward the Lobos islands. The temperatures maintained their position between 20° and 21° but, in approaching the land, the presence of two other tongues of warm water with colder water on each side was detected. This finding is in variance with that of GUNTHER who figures a solid wedge extending offshore. According to SCHWEIGGER, however, these warm-water tongues are to be found quite regularly each year.

In summarizing our observations of the period we may emphasize the following points:

(1) From January to June, 1941, warm-water areas of extent and high temperature never before reported were found.
(2) Onshore temperatures were from 5° to 10° C higher than normal.
(3) This condition was present from the Ecuadorian Border to the Chilean Border.
(4) The water was offshore blue or discolored blue instead of the normal green except in the bays.
(5) No evidence of upwelled water or upwelling was found.
(6) No evidence of a highly developed El Nino occurrence was found.
(7) The hot water was accompanied by hammerhead-sharks, manta-rays, flying-fish, dolphins and large numbers of tuna.
(8) Plankton-samples show a shift from normal types of copepods and phyto-planktonic types to Sagittae and pelagic salps (from VOGT'S samples).
(9) Wind-direction at Chincha Island was from south- to southwest-sector 74 per cent of the time instead of the usual south to southeast.
(10) Warm-water tongues of paramount importance to the fisheries were found.

The only logical reason for these changes can be laid to the shift in the prevailing winds. It has been shown by other workers that winds remote from a given area can cause great changes. It is my belief that all of the high-temperature surface-waters were of oceanic origin (that is, the clear, blue offshore-type). The shift in the winds caused a cessation of upwelling and also pushed in the oceanic waters. With a resumption to normal, upwelling again returned and the oceanic waters were dissipated.

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U. S. Department of the Interior,
Fish and Wildlife Service,
Washington, D. C.

PACIFIC CAMPAIGN OF THE SCHOONER ASKOY--DARIEN, COLOMBIA, ECUADOR

Robert Cushman Murphy
(Abstract)

This contribution is primarily an exhibit of kodachrome motion-picture film, and an accompanying narrative, rather than a report on scientific results.

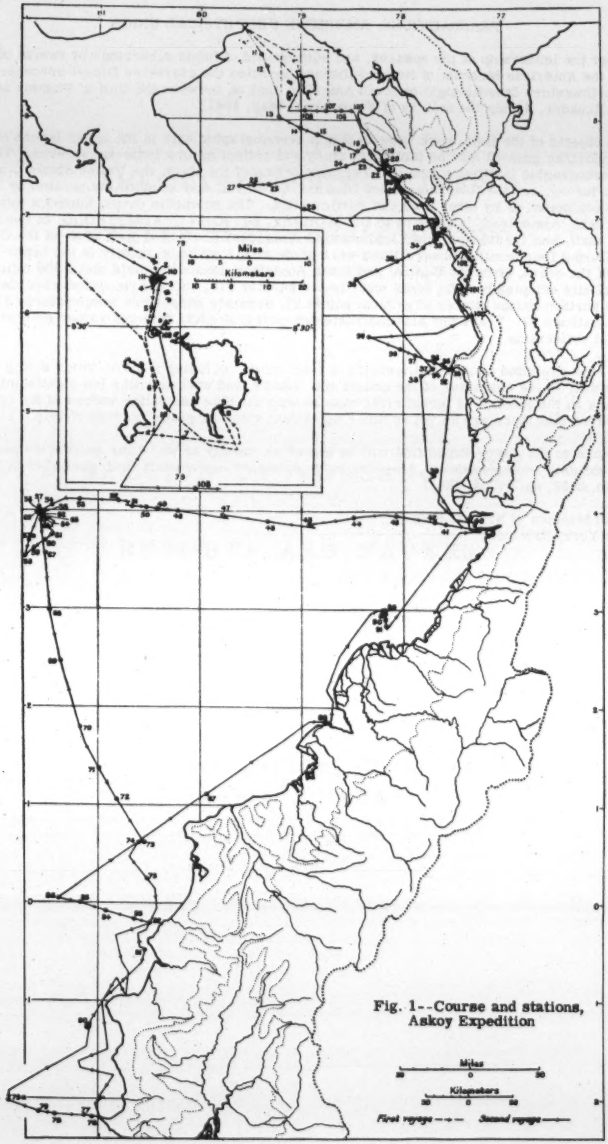

Fig. 1--Course and stations, Askoy Expedition

Under the leadership of the speaker, and with the aid of funds subscribed by twelve of his friends, the American Museum of Natural History operated the chartered Diesel schooner Askoy in the northwestern oceanic bight of South America, that is, between the Gulf of Panama and western Ecuador, during the months of February to May, 1941.

The objects of the field-work were to obtain oceanographic data in the upper layers of the sea and to undertake general marine biological study and collecting in a little-known area. The Woods Hole Oceanographic Institution, the Hydrographic Office of the Navy, the United States Coast and Geodetic Survey, and the Governments of Panama, Colombia, and Ecuador cooperated by lending valuable equipment or by other forms of participation. The scientific corps, among a total crew of seven men, comprised, in addition to Dr. MURPHY, Dr. JOHN C. ARMSTRONG, of the American Museum staff, and Lieutenant (now Lieutenant-Commander) EDUARDO FALLON, of the Colombian Navy. During four months, observations were made at 113 stations, mostly in the upper 150 to 200 meters of the ocean, from the Central and South American coasts to points about 300 miles to the west. Salinity samples brought home and titrated number 210, bathythermograph records 83, separate surface-temperatures at critical points 97, separate subsurface temperatures 51, plankton-catches 77. There are also instrumental meteorological data and rather extensive zoological collections.

The film exhibited showed the methods of field-work, including shallow-water diving operations, as well as the character of the coasts and islands, and such familiar but significant oceanic phenomena as the junction of turbid river-waters with the blue and saline waters of the open ocean. It is believed that there are as yet no other equivalent cinematograph records of this.

Reports on the Askoy Expedition will be issued as rapidly as war-time exigencies permit study of the data and specimens. A preliminary statement has already been published in Science [v. 94, No. 2429, pp. 57-58, 1941].

American Museum of Natural History,
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AMERICAN GEOPHYSICAL UNION

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REPORTS AND PAPERS

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A SYNTECTONIC INTRUSION IN EASTERN ALABAMA

H. Richard Gault

The Pinckneyville quartz-diorite complex underlies an area in eastern Alabama extending from the Coosa River in northwest Elmore County northeast through Coosa and Tallapoosa counties into Clay County.

Dark-gray, coarse-grained quartz-diorite gneiss constitutes the major part of the complex, but there are smaller amounts of granodiorite and granite gneiss. Hornblende biotite gneiss also occurs and is considered to represent either metamorphosed basic sills and dikes intruded earlier than the quartz-diorite complex or possibly original sediments. Schist septa lie within the complex and are usually parallel to the regional strike. The sequence of intrusion as interpreted from inclusions and petrographic data is quartz-diorite--granodiorite--granite. Small but persistent amounts of allanite and epidote are characteristic of the rocks of the complex. The texture is subporphyritic and shows evidence of protoclastic deformation.

A northeast-southwest trend of inclusions, foliation, lineation, and contacts dominates. Primary-flow structures are shown in the orientation of inclusions and micas. Secondary structures were superposed on the original flow structures shortly after intrusion and prior to complete consolidation. The intensity of the planar structures in the gneiss grades from strong to indistinct or lacking and decreases from east to west. Structures in schist inclusions indicate that some folding had taken place prior to intrusion.

Thin pegmatite, granodiorite, and granite dikes are common. All are parallel to or cut the regional strike at small angles.

The petrographic boundary between gneiss and schist is always sharp. On a large scale, the gneiss structures are essentially parallel to the contacts, but slight to marked discordant relations are found at many localities. The schist structures usually parallel the contacts.

Petrofabric analysis confirms the structural field-observations. The mica fabrics are ac-girdles and are most complete where the foliation is weakest. Microscopic S-planes do not always coincide with the observed foliation. The quartz fabrics are also ac-girdles but are not as well developed as the mica girdles. Quartz orientations cannot always be related to known S-planes.

It is concluded that the Pinckneyville quartz-diorite complex represents a syntectonic intrusion, that is, that intrusion took place during the folding of the region. The shape of the intrusion was controlled to a large extent by the wall-rock structures which had developed earlier. The rocks show both igneous and metamorphic characteristics because the intrusion took place under regional metamorphic conditions.

Washington, D. C.

ORIGIN OF THE AYER GRANODIORITE IN THE LOWELL AREA, MASSACHUSETTS

Richard H. Jahns

(Published with the approval of the Director, Geological Survey,
United States Department of the Interior)

The elongate stock of Ayer granodiorite exposed north and west of Lowell, Massachusetts, is reasonably typical of the many bodies of granitic rocks in the central and north-central parts of the State. It lies within a terrane composed predominantly of steeply tilted, thinly interbedded quartzite and biotite schist, and many of its structural relations superficially suggest for it a metasomatic origin, involving the quiet replacement of preexisting bedded and foliated rocks by invading fluids of magmatic derivation. The elongation of the stock and a distinct foliation characteristic of the granodiorite itself are both essentially conformable with country-rock structure, and the contacts, wherever seen, also appear to be concordant. This general parallelism is further emphasized by a consistent orientation of numerous tabular inclusions, the edges of most of which have been obscured by reaction with the igneous material. Moreover, apparent transitions from country-rock into granodiorite in a direction parallel to their structural trends occur at

several places. Dikes and lenses of pegmatite are abundant within and adjacent to the granodiorite body.

Despite these and other features suggestive of a metasomatic origin, close scrutiny of all available outcrops has revealed considerable evidence to the contrary. That at least large portions of the granodiorite were formed from mechanically injected molten material is demonstrated by the occurrence of cross-cutting apophyses, of contact-breccias with variously oriented fragments of several rock-types in a matrix of the granodiorite, and of local but acute deformation in the country-rock that is ascribable only to the action of a nearby magma. Contacts between granodiorite and country-rock are everywhere sharp, and the apparent transition-zones mentioned above are in reality zones of clear-cut lit-par-lit injection, in which the granodiorite appears within the country-rock as long, sharply defined septa.

The foliation in the igneous rock, which decreases in intensity away from the contacts, is interpreted as a primary-flow structure, rather than as relict bedding or foliation of a metasomatically replaced country-rock, chiefly because of the following features:

(1) The foliation is strictly parallel to the contacts, whether with bedded metasedimentary or massive igneous rock; it does not form isoclinal folds or other flexures characteristic of much of the country-rock.
(2) Both linear elements and drag folds in the country-rock metasediments ordinarily plunge gently northward, locally gently to the south; linear elements in the granodiorite plunge very steeply.
(3) Inclusions of schist and quartzite have been rotated and alined in accord with the granodiorite foliation, for the linear elements within them have no consistent orientation; the foliation trends around, rather than through the inclusions.
(4) Thin, uniform, and continuous bands like those found in the Chelmsford granite are absent from the granodiorite, but features readily interpretable as flow-schlieren are common.

Structural trends in the country-rock indicate that it has been thrust aside, rather than engulfed or replaced by the granodiorite, and that relatively little of it was lost in the process.

Microscopically the granodiorite consists of andesine, microcline, quartz, biotite, hornblende, and accessories. Crystallization-zoning of the plagioclase is common, but core-and-rim structures are absent. Myrmekite is present, but there is no evidence of appreciable albitization. The texture in general is that of an ordinary igneous rock that has been mildly sheared and somewhat affected by deuteric action during the last stages of its crystallization.

It is concluded, chiefly on the basis of field-evidence, that the Ayer granodiorite stock near Lowell is a concordant body formed by the crystallization of a relatively "wet", but mechanically irrupted magma. Despite some apparently attractive evidence, the concept of its immediate origin through metasomatism of preexisting schist and quartzite is rejected, primarily because of more significant features that demonstrate a considerable amount of upward movement within the mass before its consolidation.

U. S. Geological Survey,
Washington, D. C.

INTRUSIVE ROCKS IN THE BLUE RIDGE PLATEAU, VIRGINIA

Anna J. Stose

(Abstract)

An injection complex of early pre-Cambrian age is exposed in the Elk Creek anticline in Grayson County, Virginia. There, sedimentary rocks and diorite have been intruded by the Striped Rock and the Carsonville granites. The granites have metamorphosed, injected, reacted with, and replaced the older rocks to form many mixed types. This injection complex is part of a large area of similar rocks that form the core of the Catoctin Mountain-Blue Ridge uplift in Virginia, and is much older than the overlying volcanic series of later pre-Cambrian age.

U. S. Geological Survey,
Washington, D. C.

ORIGIN OF THE CHELMSFORD GRANITE, MASSACHUSETTS

L. W. Currier

No abstract or manuscript of this paper was received.

U. S. Geological Survey,
Washington, D. C.

STRUCTURAL OBSERVATIONS INDICATING AN INTRUSIVE ORIGIN FOR THE BEARTOOTH BATHOLITH

E. C. H. Lammers

No abstract or manuscript of this paper was received.

Washington and Lee University,
Lexington, Virginia

THE PELHAM GNEISS DOME, MASSACHUSETTS

Robert Balk

(Abstract)

(Published with the permission of the Director, U. S. Geological Survey, Department of the Interior, and the Commissioner of Public Works, Commonwealth of Massachusetts)

The Pelham gneiss dome in central-northern Massachusetts, east of the Connecticut Valley, measures about 27 by 7 miles. Its axis strikes north-south, and the northern end is three miles south of the New Hampshire Border. Gneissic foliation is remarkably well developed throughout the dome. The planes lie subhorizontal along the axis, and on the symmetric western and eastern slopes the dip rarely exceeds 45°.

In the northern portion, which has recently been mapped for the Massachusetts Cooperative Geologic Project, the dome is composed of a sedimentary and an igneous phase. The sedimentary gneiss is composed, in the approximate order of decreasing abundance, of quartz, biotite, muscovite, plagioclase, a little potash feldspar, and accessory minerals. Minor amounts of quartzite and amphibolite are associated with this gneiss. The igneous phase is composed of quartz, potash feldspar, oligoclase, biotite, hornblende, and accessories (epidote, magnetite, sphene, apatite). Potash feldspar exceeds soda-lime feldspar in amount; microcline crystalloblasts, up to eight inches across, are common; and in places hornblende and magnetite also form crystalloblasts, up to one inch across. An equigranular border phase lacks crystalloblasts, but contains also a high amount of potash feldspar.

The orthogneiss forms a number of concordant sheets and sills in the sedimentary gneiss. Only two small, discordant dikes have been found in about 80 square miles that have been mapped in detail. The floors of the sills, well exposed in escarpments, reveal gradational zones, about 15 to 30 feet thick, in which the amount of plagioclase and biotite of the flooring paragneiss decreases, and potash feldspar increases. Scattered throughout the sills are lenses and thin "films" of quartzite and amphibolite. Wide-spread, thin films of biotite in the sills may thus be suspected to be of non-igneous origin. Despite these features suggesting metasomatic origin of the sills, the igneous-looking gneiss has not moved vertically upward in the dome, but must have advanced concordantly, along gently inclined or even horizontal planes. A detailed investigation is contemplated to determine how rapidly the amount of potash feldspar increases vertically in the contact-zones of the sills. The width or narrowness of these zones is thought to furnish a good criterion to ascertain the degree of viscosity of the introduced material.

Structurally, the dome differs in many respects from dome-structures of non-foliated granites. It lacks border-zones with primary crushing or cataclasis; even in the core of the dome, paragneiss is abundant. Although lineation, trending north to north-northeast to south-southwest, is uniformly developed in the dome, this structure is hardly anywhere more pronounced than the foliation. There is a noteworthy lack of cross-joints, perpendicular to the lineation; and inward-dipping

north-south joints are also scarcer than might be expected in so symmetric a dome. The lineation in all phases of the gneiss appears to have originated through plastic flow, subsequent to isoclinal folding and slipping along the limbs of folds in the paragneiss.

Mt. Holyoke College,
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BASEMENT VOLCANOLOGY

Augustus Locke

(Abstract)

The maps of the Sierra Nevada Region have gained enough detail to individualize steep granite-structures, some of which must have channelled heat to the surface. MAYO, who mapped 4,000 square miles, 1930-1940, in the High Sierras, found many such structures in the forms of hooks or whorls, the outcrops of steep drag-folds, successive in time and place. One of these, in Jawbone Canyon, carries porphyry made after the upper part was eroded away. This is a kind of channel which, with sufficient heat-energy, can make a volcano.

At Goldfield, BILLINGSLEY, LOCKE, and MAYO recognized a similar structure in porphyry cover rocks.

Illustrations included maps of Jawbone Canyon and Goldfield and a projection showing an idea of a basement-granite channel with surface-escape.

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ORIGIN AND STRUCTURAL RELATIONSHIPS OF THE IGNEOUS MEMBER OF THE LIVINGSTON FORMATION, MONTANA

Willard H. Parsons and Marcellus H. Stow

In southwestern Montana north of the Beartooth Mountain uplift and between the north-flowing Boulder and Stillwater Rivers is an area of volcanic rocks previously known as the agglomerate member of the Livingston Formation [see 1 of "References" at end of paper]. The name Livingston Formation was first applied to about 7,000 feet of sandstones, shales, and conglomerates north and east of Livingston, Montana, but later studies have resulted in considerable remapping of the Livingston as Claggett, Judith River, Bearpaw, Lennep, Lance, and Fort Union formations. Only the original agglomerate member, better called the igneous member, now remains in the Livingston. These volcanic rocks are one unit of the many upper Cretaceous extrusive rocks in western Montana.

This igneous member contains volcanic breccias, tuffs, a few vent-agglomerates, and rare lava-flows near the Beartooth Mountain front but grades eastward, northward, and westward into volcanic sandstones and conglomerates, and finally into Judith River, Bearpaw, Lennep, and Lance sediments. Most of these volcanic rocks are andesitic. Several small plugs filled with vent-agglomerate indicate that the entire volcanic series originated from a large number of small vents. Original bedding has been largely destroyed by dry avalanches and mud-flows but outward from the extrusive centers bedding characteristic of stream-deposited material is present.

Two laccoliths varying from diorite to monzonite and a radiating series of narrow, vertical, andesite dikes cut the extrusive rocks near the vent-structures. These laccoliths have tilted the early volcanic braccias but are overlain unconformably by other later breccias.

The volcanic series lies unconformably on Judith River, Eagle, and older sediments. The earliest and dacitic volcanic breccias are overlain with a slight angular unconformity by the andesitic breccias. These early dacitic breccias and tuffs contain a fossil flora identified as Judith River in age. The Hell Creek member of the Lance formation overlies the volcanic sandstones and conglomerates with a conformable, gradational contact.

The sequence of events may be summarized as follows:

(1) First eruptions (dacitic) in upper Judith River time, very local in extent and with contemporaneous sedimentation in adjacent areas
(2) Local warping or doming and slight erosion
(3) Eruption of andesitic breccias of Bearpaw age resting unconformably on dacitic breccias and Judith River, Claggett and Eagle sediments
(4) Intrusion of laccoliths, doming and erosion
(5) Further extrusion of andesitic breccias and intrusion of dikes in Lennep time; these breccias rest unconformably on the older (Bearpaw) eroded volcanic breccias and laccoliths
(6) Lance sedimentation (Hell Creek member) conformably on volcanics
(7) Main Beartooth thrusting

Studies of the Lance and Fort Union sediments north and east of the Beartooth Mountain uplift show differences in the heavy mineral content [2]. In an eastern depositional basin, east and north of the Beartooth uplift as far as a north-south line just west of Columbus, Montana, the Lance and Fort Union contain no hornblende or augite but red garnet, staurolite, and kyanite are present in the upper Fort Union. In a western depositional basin, north of the Beartooth uplift and west of Columbus, the Lance and Fort Union contain augite and a little hornblende throughout but no staurolite or kyanite. The source of the garnet, staurolite, and kyanite must have been pre-Cambrian metamorphics in the Beartooth thrust-mass. These facts indicate that pre-Cambrian rocks were not exposed in the western part of the Beartooth uplift in Lance and Fort Union time, as they were to the east, because (1) thrusting was less intense in the western section and was chiefly towards the south with a dip slope to the north and (2) Livingston volcanic rocks were piled on this dip-slope and prevented erosion from cutting down into pre-Cambrian rocks. The source of the augite and hornblende in the Lance and Fort Union of the western area was the igneous member of the Livingston formation.

Acknowledgments--The writers are duly grateful for financial assistance from the Penrose Bequest of the Geological Society of America and from the Yellowstone-Bighorn Research Association.

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THE RELATIONS OF THE ANORTHOSITE AND GABBRO IN THE LAKE SANFORD AREA, NEW YORK

R. C. Stephenson

(Abstract)

In a detailed study of the area of the Lake Sanford titaniferous magnetite deposits some interesting relations between anorthosite and gabbro came to light. Gabbro can be found grading into the anorthosite, showing the consanguinity of the two rocks, but in a few places the gabbro is intrusive into the already consolidated portions of the anorthosite.

Both the anorthosite and gabbro show foliation, with local exceptions in the anorthosite. Much of the coarser anorthosite shows a unique flow-structure. The side pinacoids of the tabular plagioclase crystals in this type of structure lie parallel to the axis of flowage in the magma, assuming any orientation from 0° to 360° around this axis. The flow-structures in the area are swirling, indicating the turbulent conditions which probably existed in the central portions of the Adirondack anorthosite mass during the period of consolidation. The coarse anorthosite grades laterally into finer anorthosite and gabbroic anorthosite with no perceptible boundaries, the anorthosite being more gabbroic where the bends in the foliation are most intense. In several localities, where the curvature is the most extreme, there has been a concentration of gabbroic titaniferous magnetite. The Cheney Pond ore body is a lense-like conformable mass of ore which occurs in a spherical gabbro body similar to those described elsewhere in the Adirondacks by Dr.

BALK. This body grades into gabbroic anorthosite to the east of Cheney Pond but intrudes anorthosite on the southwest side.

The similarity in composition of the anorthosite and gabbro further substantiates the intimate structural relations. The texture of the rock and the relative per cents of the minerals provide the basis for division. The plagioclase of the rock ranges from An_{35} to An_{65}. Augite, hypersthene, hornblende, magnetite, and ilmenite are the other important rock-minerals. The anorthosite is a relatively pure plagioclase rock which may vary in texture from a medium grain to an extremely coarse grain, with plagioclase phenocrysts up to two to three inches in length in a medium-grain groundmass. The plagioclase phenocrysts show effects of early granulation and fracturing, traces of which are mostly obliterated by subsequent reworking of the deformed crystals. The groundmass may be pure plagioclase or may grade into a somewhat gabbroic material by an increasing percentage of femic minerals. All gradations from anorthosite to gabbro may be seen in the field. The plagioclase phenocrysts decrease in number as the groundmass becomes more gabbroic, giving rise to the large amounts of gabbroic anorthosite in the area. The gabbro is a medium-grain rock in which there are local bands of titaniferous magnetite parallel to the foliation.

The early deformed plagioclase phenocrysts suggest that the process of filter-pressing was active in the differentiation of the rocks of this area. The writer believes that the anorthosite and gabbro in the Lake Sanford Area differentiated from a gabbroic anorthosite magma, with gabbroic interstitial magma being pressed from the mush of accumulated plagioclase crystals as the anorthosite was being emplaced. Further differentiation within the gabbro led to the late concentration of ilmenite and magnetite which form the ore-bodies of the area.

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A COURSE OF CONCENTRATION OF IRON, TITANIUM, AND PHOSPHOROUS IN MAGMATIC DIFFERENTIATION

A. F. Buddington

(Abstract)

There is a rough parallelism between the course of variation of composition of successive fractions of magma as shown by (1) successive stages in the crystallization of certain basalts (phenocrysts, groundmass, interstitial glass), (2) successive superposed layers of certain stratiform sheets such as the Skaergaard, Bushveld, Duluth, etc., (3) successive members of certain related series of successive intrusions. If these are interpreted as due to differentiation the trend of variation in composition is from gabbroic or noritic in the direction of concentration of iron, titanium, and phosphorous up to a certain maximum (melanocratic gabbro facies) followed by a sharp decrease of these constituents and the development of a salic residuum. This is suggested as possibly one line of magmatic differentiation though it is recognized that there are others as for example by way of augite pyroxenites to end in ilmenite-magnetite deposits without phosphorous, and so forth.

Princeton University,
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THE NABESNA GOLD-DEPOSIT, ALASKA

R. G. Wayland

(Preliminary abstract)

The gold-deposit of the Nabesna mine in the northern border of the Wrangell Mountains occurs in a geologic environment more typical of some tungsten or base-metal ores than of gold ores. A small stock of quartz diorite has invaded Triassic limestones with the development of considerable tactite and of a few bodies of magnetite and others of pyrrhotite. In the recrystallized limestone near these bodies, following a system of fractures and the contacts between different rock-types, are auriferous pyrite veins.

The principal mine was mapped during the last month of its ten-year life, affording a "post mortem" of its genesis, zoning and structural control.

Army and Navy Munitions Board,
Washington, D. C.

THE FIELD OF STABILITY OF PYRRHOTITE

Einar Jensen

(Abstract)

The melting relations in part of the system Fe-S on both sides of the composition FeS (troilite) were studied by the method of differential thermal analysis. To prevent oxidation and loss of sulphur the mattes were sealed in specially designed, evacuated, silica-containers.

The results are: At the melting-temperature iron dissolves only in very small amounts, if at all, in solid troilite. The eutectic iron-troilite is at 988° and a gross composition 68.5-69.0 per cent iron. Troilite melts over an interval of about 100°, ending at 1171°.

Solution of sulphur in troilite, forming pyrrhotites, raises the melting-temperature and narrows the melting-interval, until a maximum melting-temperature of 1191° is reached at 61.7 per cent iron, corresponding to $FeS_{1.08}$ or $Fe_{12}S_{13}$, which melts sharply as if it were a pure compound. Addition of still more sulphur lowers the melting-temperature, and melting again takes place over an interval. No transformations are found in pyrrhotite above 800°.

These data, together with data from the literature, were used for constructing a diagram giving the field of stability of pyrrhotite.

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FORMATION OF AEGIRINE-AUGITE AND ARFVEDSONITE BY REACTION

R. R. Coats

(Abstract)

On the northern border of the granite mass of Ear Mountain, Seward Peninsula, Alaska, a thin sill of alaskitic composition has intruded a diopside-bearing metamorphosed sediment. The diopside has been taken up by the sill, and has reacted with it to form aegirine-augite. The aegirine-augite has been preserved unchanged in the fine-grained margin of the sill, but in the coarser part it has been attacked, presumably by deuteric fluids, to form arfvedsonite.

U. S. Geological Survey,
Washington, D. C.

AMERICAN GEOPHYSICAL UNION

TWENTY-THIRD ANNUAL MEETING

SECTION OF HYDROLOGY

REPORTS AND PAPERS

Washington, D. C.
April 3, 4, 1942

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SECTION OF HYDROLOGY

WASHINGTON MEETING, APRIL 3, 4, 1942

REPORT OF COMMITTEE ON RUNOFF, 1941-42

W. G. Hoyt, Chairman

During the early part of the decade just ending there were certain events which have had pronounced influence on investigations and studies of runoff during the last eight- or ten-year period, a period during which I think you will agree that hydrology has reached great heights. Since war activities crowd the future and may take our minds off the past, I wish to comment briefly upon some of the outstanding past events in this report of the present Committee on Runoff.

This meeting falls on the tenth birthday (April 3, 1942) of the unit-hydrograph. Ten years ago this April, L. K. SHERMAN published in the Engineering News Record the first presentation of the unit-hydrograph theory under the title "Stream-flow from rainfall by the unit-graph theory." I know of no single concept which has been so widely used since its presentation as that of the unit-hydrograph. It has been found to have been an invaluable tool in the countless studies and problems involving channel-flow in all its forms and it has been a foundation for much of our present concepts of channel-storage. In spite of certain imperfections the theory has stood the test of time and many engineers in many organizations have made outstanding use of the theory in practical problems of many kinds. Messrs. BERNARD, McCARTHY, MORGAN and HULLINGHURST, SNYDER, LANGBEIN, and others have made important contributions in writing concerning development, application and correlation, and much discussion (at present unpublished) has been prepared by other investigators. Like many hydraulic principles it has its limitations and imperfections which are more or less fully recognized by those who have had to deal with its practical application. It is unnecessary to list the imperfections of the theory. It is desirable to point out, however, that the advantages of its adaptability to practical problems far outweigh any difficulties arising from its imperfections. The hydrologist owes a large debt to Mr. SHERMAN. I am taking the liberty of suggesting herewith that the Committee on Runoff might well take sponsorship of a project to review thoroughly our present knowledge of the unit-hydrograph with a view to the standardization as far as possible of methods of analyses, applications, and derivation of correlations. The unit-hydrograph began a decade not starved for ideas. The role of infiltration and natural stream-channel storage in the hydrologic cycle were fitting additions to the science as were also R. E. HORTON'S notable contribution "One hundred and one" and others. That many others were busy too is evidenced by the growth of the Transactions from a thin 125 pages ten years ago to a fat 600 pages in 1941.

Other events of the decade, which I believe have also had a profound and certainly beneficial influence on hydrologic investigations, relate to the close coordination between private consulting hydraulic engineers and hydraulic engineers and hydrologists in public service. These close relationships had their inception, as you may remember, eight years ago through the appointment of two outstanding groups of private engineers to act as consultants and advisers on two projects organized in the United States Geological Survey and sponsored by what was then the Mississippi Valley Committee, now the Water Resources Committee of the National Resources Planning Board. One of these projects related to floods, the immediate technical details of which were under the direction of C. S. JARVIS, and the other project related to rainfall-runoff analyses, under the technical supervision of the speaker. In connection with these two investigations the Federal staff had at all times the expert advice and guidance of such private consultants as BARROWS, HORNER, HORTON, MEYER, SAVILLE, SHERMAN, and others. It is of interest to point out that following completion of these two studies, these and other consultants have carried on in a similar capacity in connection with the activities of the Water Resources Committee, Soil Conservation Service, and other Federal agencies. It is significant to point out also that the majority of the staff who were engaged in the two original studies have continued their research-activities in various capacities throughout many Federal agencies and have made outstanding contributions during the decade. I think it is unquestionably true that the stimulation received from the interchange of ideas has spurred all Federal investigators on to greater achievement. I would surmise that perhaps in some respects the stimulation has also benefitted investigators outside

the Government service. Here again, from the viewpoint of Federal workers, acknowledgment of a debt is fitting.

On the credit side mention should also be made of the close cooperation between the Section of Hydrology, college staffs, and national societies such as the Society for the Promotion of Engineering Education and the American Society of Civil Engineers, as witnessed by the two outstanding hydrologic conferences, one held at Iowa City during June 1939 and one at Penn State during July 1941, the success of which rested so much on the activities of Professors LANE, MAVIS, and STRAUB. Last but not least in the activities which have furthered our knowledge of runoff-phenomena has been the extremely close cooperation between the technical staffs of the many Federal agencies working on hydrologic problems. Although this cooperation may not at all times have extended to all the administrative heads, the groundwork for many important hydrologic conclusions has been laid in continuous informal contacts between the various research-workers. I feel that members of the Committee on Runoff have at all times endeavored to promote the spirit of cooperation and record thereof seems appropriate herein.

Reverting now to the current activities of the Committee on Runoff, I announce with regret the sudden death on March 16, 1942, of Mr. JOSEPH JACOBS, Consulting Hydraulic Engineer of Seattle, and a member of the Committee. Although an extremely busy man Mr. JACOBS always found time to interest himself in activities of the Committee.

The activities of the members of the Committee on Runoff have as usual been informal throughout the year. I believe, however, that all members of the Committee without exception have contributed substantially during the year to our knowledge of runoff-phenomena. This, I believe, is evidenced by the numerous original articles and discussions.

The Chairman, working informally with Messrs. J. M. DAVIDSON of the Soil Conservation Service, MERRILL BERNARD of the Weather Bureau, G. A. HATHAWAY of the United States Engineer Department, and I. H. SIMS of the Forest Service, made a preliminary compilation of "Principal Federal sources of hydrologic data," some 600 copies of which were mimeographed by the Water Resources Committee and given wide circulation. The Subcommittee on Hydrologic Data and Research of the Water Resources Committee, on which our Committee is represented, are now soliciting constructive criticism of all recipients of the preliminary report.

During July Professor MAVIS, a member of the Committee and head of the Department of Civil Engineering at Pennsylvania State College, conducted a hydrologic conference under the sponsorship of Penn State College, the Section of Hydrology of the American Geophysical Union, the Society for the Promotion of Engineering Education, and the Committee on Hydrology of the American Society of Civil Engineers. This was probably the most outstanding hydrologic conference held during the year. Copies of the proceedings of the Conference are practically ready for distribution.

Mr. SNYDER reports that the Weather Bureau has continued its development of river-stage forecasting methods based on practical application of modern hydrologic concepts. The existing forecasting procedures for the Connecticut, Kanawa, Middle Ohio, Chippewa, Iowa, Blue, Republican, Sacramento, and Colorado (Texas) river-basins have been extended during the past year. The recent establishment by the Bureau of seven regional administrative offices now provides a hydrologic engineer in each region to assist the local river-district officials in their work with special emphasis on the formulation of river-forecasting methods.

WALDO E. SMITH of the Soil Conservation Service and his associates have been especially active in making the results of the numerous experiment-stations and research-centers available to the public through the publication of hydrologic bulletins. As you know, during November 1941, Hydrologic Bulletin No. 1 summarizing the rainfall- and runoff-observations during 1939 on the Coshocton Area in Ohio was published, and Bulletin Nos. 2 to 5 covering observations at Waco (Texas), Hastings (Nebraska), and Coshocton (Ohio) are in the final stages of publication.

Purely from the point of hydrologic research, two projects are underway in the Geological Survey. The first relates to a compilation of basin-characteristics for a very considerable part of the northeastern United States from Ohio and Pennsylvania through Maine. The second relates to a compilation of flood-runoff volumes for all major winter and non-winter floods for every gaging-station in the United States through 1939. Both of these studies have been carried on as part of a Works Projects Administration project at Pittsburgh, sponsored jointly by the Weather Bureau and the Geological Survey.

In view of the fact that the preliminary compilation of "Principal Federal sources of hydrologic data" includes description of all experimental areas, watersheds, forests, and demonstration projects and the bibliography prepared by the Section of Hydrology contains references to all runoff-articles prepared during the year, additional references are not made a part of this report.

I would, however, like to call the attention of the Section of Hydrology to the completion of a report by the Committee on Floods of the Boston Society of Civil Engineers. This Committee was appointed in 1936 by Professor H. K. BARROWS, President of the Boston Society of Civil Engineers and a member of our Committee on Runoff. The final report of the Committee was published in the Journal of the Boston Society of Civil Engineers [January 1942]. The report, when read in connection with the pioneer flood-report by the Boston Society, published in 1930, contains invaluable information concerning the flood-hydrology of New England.

Hydrologically and meteorologically the conditions throughout the United States during the past 12 months have been decidedly upside down. The arid and semiarid Southwest and also the famous dust-bowl, about which we heard so much a few years past, have been drenched with repeated rains and the so-called humid East has experienced 12 consecutive months of drought. Brief descriptions of the droughts and floods have been published monthly in the Water Resources Review prepared by the Geological Survey and are therefore not included herewith.

The cooperation and support of all members of the Runoff Committee is herewith acknowledged. Its members are: H. K. BARROWS; MERRILL BERNARD; E. S. CULLINGS; R. S. GOODRIDGE; G. A. HATHAWAY; W. G. HOYT (Chairman); JOSEPH JACOBS (deceased); F. T. MAVIS; H. S. RIESBOL; WALDO SMITH; F. F. SNYDER; and H. G. WILM.

REPORT OF COMMITTEE ON PHYSICS OF SOIL-MOISTURE, 1941-42
(Soil-Moisture Conditions and Phenomena in Frozen Soils)

N. E. Edlefsen, Chairman

The membership of the Committee is as follows:

Dr. L. D. BAVER, North Carolina State College, Raleigh, North Carolina
Dr. G. B. BODMAN, University of California, Berkeley, California
Dr. RICHARD BRADFIELD, Cornell University, Ithaca, New York
Mr. S. J. BUCHANAN, United States Waterways Experiment Station, Vicksburg, Mississippi
Dr. T. F. BUEHRER, University of Arizona, Tucson, Arizona
Dr. I. A. DENISON, National Bureau of Standards, United States Department of Commerce, Washington, D. C.
Dr. WILLARD GARDNER, Utah Experiment Station, Logan, Utah
Dr. GLENNON GILBOY, Massachusetts Institute of Technology, Cambridge, Massachusetts
Dr. O. W. ISRAELSEN, Utah State Agricultural College, Logan, Utah
Dr. L. B. OLMSTEAD, Bureau of Plant Industry, United States Department of Agriculture, Washington, D. C.
Dr. L. A. RICHARDS, Bureau of Plant Industry, United States Department of Agriculture, Riverside, California
Dr. F. J. VEIHMEYER, University of California, Davis, California
Mr. E. A. WILLIS, Bureau of Public Roads, United States Department of Agriculture, Washington, D. C.
Dr. N. E. EDLEFSEN, University of California, Davis, California

The annual report of the Committee this year, as has been the custom in the past, is intended to be a symposium on some aspect of the physics of soil-moisture. The following paper was prepared to serve as a nucleus of the report. The idea back of the paper was to stimulate discussion on the subject. The paper was sent to each member of the Committee and to a selected list of individuals interested in soils with a request for their comments, opinions, and criticisms, together with their references to pertinent data. The original paper, as well as the comments and discussions by various individuals following the paper, are published herewith verbatim without being edited in any way by the Chairman. In a few replies, the discussion was part of a letter, and, in these cases, the Chairman has taken the liberty of deleting parts of the letter not pertinent to the discussion.

SOIL-MOISTURE CONDITIONS AND PHENOMENA IN FROZEN SOILS

Alfred B. C. Anderson, Joel E. Fletcher, and N. E. Edlefsen

In this article we shall discuss briefly some of the general characteristics of observations in laboratory and field related to freezing of soil-moisture. We shall also consider the basic thermodynamic theory requisite to an interpretation of these observations in relation to the movement of moisture associated with frozen soils.

Experimental methods of measuring the temperature at which soil-moisture freezes

Two methods are commonly used in volume-freezing-point-moisture-content investigations on soils. In one (often called the BECKMANN technique, since the procedure followed is largely that used by BECKMANN in determining the freezing-point of solutions) the soil-sample is prepared at a given moisture-content and is placed in a vessel in which is inserted a sensitive thermometer or other temperature-measuring device. Then the temperature of the moist soil is lowered until freezing of the soil-moisture is just initiated. This temperature is then noted. A series of such measurements of the freezing-point made on separate soil-samples, each at a different moisture-content, furnishes the data necessary to construct a curve showing the dependence of the freezing-point of soil-moisture on the soil-moisture content. A typical example presented in Figure 1 for Aiken clay loam [see 2 of "References" at end of paper] (moisture-equivalent 31.5 per cent, permanent wilting-percentage 19.5 per cent) shows that with decreases of the soil-moisture content little change of freezing-point occurs until a little below the moisture-equivalent, where with further decrease of soil-moisture content, the freezing-point depression begins to decrease becoming very great in the vicinity of the permanent wilting-percentage. The curve gives the maximum temperatures (in the absence of supercooling) necessary to just begin to freeze the moisture at the different soil-moisture contents.

In the other (often called the dilatometer-method) the sample of soil to be studied is placed in a closed vessel on top of which is attached a long vertical capillary tube. More than enough water is added to saturate the soil, the amount of which is carefully determined. On top of the saturated soil is added some light oil (for example, kerosene) to fill completely all remaining space in the vessel, as well as a small part of the lower end of the capillary tube. The temperature of the vessel and of its contents is lowered until ice is formed within the saturated soil. A change from water to ice causes the contents of the vessel to expand. This expansion due to the formation of ice forces the oil up the capillary tube, which is calibrated so that the exact amount of expansion can be calculated and therefore the amount of moisture changed to ice. From a knowledge of the total amount of water in the soil and the amount of water changed to ice, the amount of water remaining unfrozen can be readily calculated. Thus by determining the amount of unfrozen moisture in the more-than-saturated soil-sample, for a series of temperatures below 0°C, we can, as with the BECKMANN method, plot a curve showing the dependence of the amount of unfrozen moisture in the soil on the corresponding soil-temperature. In contrast to the BECKMANN method though, we here obtain the entire curve from but one soil-sample. Experimental results show that the curves differ slightly but agree in their general trend.

Few attempts have been made at an investigation of the interrelations among the thermodynamic quantities describing the state of moisture for frozen soil. SCHOFIELD [6] interprets the freezing-point data secured with the BECKMANN method by means of an equation, presumably meant to be equivalent to the well-known equation (3) given below, expressing the free energy of the solvent of a solution in terms of the freezing-point depression caused by the dissolved material. Although he does not specifically state it, we may logically conclude, in view of the similarity of equation (3) to his equation, after suspected typographical errors are corrected, that he attributed the depression of the freezing-point of soil-solution entirely to dissolved material. On the other hand, since his expression is also similar to equation (21) of Case 3 below, it might be that he assumed that the water at the water-ice interface in the soil-moisture, is under a different pressure than that in the ice. That is, as the water under tension freezes out, it separates out to the higher pressure of one atmosphere. This inequality of hydrostatic pressures at the water-ice interface, when the soil-moisture is under tension is plausible, but more experimental work is necessary to substantiate it. If it is true, then the same expression would serve to give free energy of the soil-moisture at the freezing-point due both to the difference in hydrostatic pressure between the ice and moisture and to the amount of dissolved material present. The total freezing-point depression in the expression would then be the sum of that due to the hydrostatic pressure and that due to the presence of the dissolved material.

Interrelations among the thermodynamic variables of state, under different conditions of freezing soil-moisture

The total free energy Δf of the moisture at any point B, for example, in the soil-moisture is made up of a number of component free energies as follows

$$\Delta f = \Delta f_P + \Delta f_0 + \Delta f_F + \Delta f_K + \Delta f_\sigma \qquad (1)$$

Let us consider each of these in detail.

Δf_P represents the component at a point B due to hydrostatic pressure (in excess of that normally present in free, pure water under one atmosphere of pressure). Expressed in terms of the freezing-point depression ΔT_P due to the hydrostatic pressure ΔP_P, we have

$$\Delta f_P = v\Delta P_P = (\ell \Delta T_P / T \Delta v) \qquad (2)$$

where ℓ is the latent heat of fusion of the ice, Δv is the change in specific volume when ice melts, and v is the specific volume of water which is approximately unity in the CGS system. In the derivation of equation (2) it is assumed that the hydrostatic pressure ΔP_P is applied equally on both the water and the ice during freezing. If such is not the case, the proper expression for ΔP in terms of the freezing-point depression ΔT may be got from the generalized treatment taken up later.

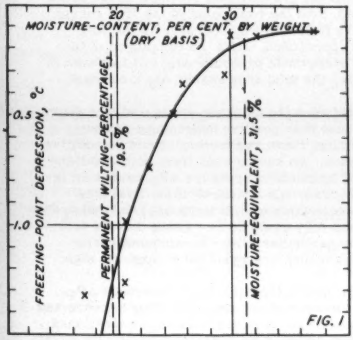


FIG. 1

Δf_0 represents the component at the point B due to the presence of dissolved material in the soil-moisture. Expressed in terms of the freezing-point depression ΔT_0 due to the osmotic pressure ΔP_0, we have

$$\Delta f_0 = -v\Delta P_0 = -(\ell \Delta T_0 / T) \qquad (3)$$

Δf_F represents the component at the point B due to the presence of a field F including the gravitational and the adsorptive fields, surrounding the soil-particle. If we consider the point A to be the datum (located in a free, pure body of water at a given point in the gravitational field) then the free energy Δf_F of a particle of water at the point B under the influence of the field F surrounding the soil-particles is given by the line-integral

$$\Delta f_F = \int_A^B F \cos\phi \, dx \qquad (4)$$

where ϕ is the angle between the element of path dx between A and B and the direction of the force F. If F and dx are in opposite directions, $\cos\phi$ is positive.

Δf_K represents the component due to the kinetic energy of the water at the point B due to its mass-movement. Expressed in terms of its streaming velocity V, we have

$$\Delta f_K = (V^2/2) \qquad (5)$$

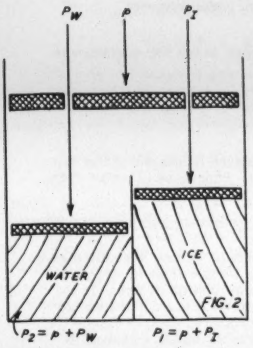
The mechanical work done on a system at constant temperature, excluding the work of expansion against a pressure, is equal to the increase in free energy of the system. Thus the increase in the total free energy of a liquid surface A when its area is increased by the amount ΔA is given by

$$\Delta f_\sigma = \sigma \Delta A \qquad (6)$$

Since, however, by convention the free energy Δf should refer to unit-mass of water and since as it stands equation (6) refers to the free energy of the element of surface ΔA, we must change the equation. Let τ represent the thickness of the surface-layer of water in which the properties are different from those of the body of the fluid. Then the average free energy per gram throughout the surface-layer may be represented by

$$\Delta f_\sigma = (\sigma / \tau \rho)$$

where ρ represents the average density of water in the layer.



Δf_S, representing the total free energy of the soil-moisture, may be expressed in terms of the vapor-pressure of the soil-moisture p and the vapor-pressure p_o of the datum as follows

$$\Delta f_S = RT \log_e (p/p_o) \qquad (7)$$

where R is the universal gas-constant. If the soil-moisture is at equilibrium in the soil, Δf_S is a constant and the same at all points throughout the liquid and vapor-phases of the soil-moisture; if the soil-moisture is in motion Δf_S will not be the same at all points.

Even though the soil-moisture is at equilibrium and therefore Δf_S is the same at all points the components of the free energy may change enormously from point to point in the soil-moisture. For example, suppose we assume that the osmotic pressure and the gravitational potential is the same throughout the liquid, then the component of the free energy due to the adsorptive field Δf_F will decrease as the soil-particle surface is approached, while the component of the free energy due to hydrostatic pressure Δf_P will increase in such a way as to keep the total free energy Δf_S a constant.

Equations (2) and (3) indicate an important relation between the freezing-points and free energies of soil-moisture. It is sometimes thought that because both positive hydrostatic pressure and dissolved material lower the freezing-point of a solution, these two factors should be additive in producing changes in the total free energy of the solution. As can be seen from both equations (2) and (3), however, this is not the case. An increase of hydrostatic pressure ΔP_P causes an increase, whereas an increase of the osmotic pressure ΔP_0 causes a decrease of the total free energy of the soil-moisture. Thus, for example, the concentration of dissolved material and hydrostatic pressure in the solution might be such that ΔT_P and ΔT_0 would be so related that the total change in specific free energy Δf_S would be zero. In this particular case, the component free energies produced by hydrostatic pressure and osmotic pressure are equal but of opposite sign.

Equation (2) for the component of the free energy Δf_P, due to the hydrostatic pressure ΔP_P, presupposes that the soil-moisture upon freezing under the hydrostatic pressure ΔP_P is converted into ice which also is under the same hydrostatic pressure ΔP_P. It is conceivable, as mentioned previously, that such is not always the case. For example, suppose we consider a relatively moist soil where the major portion of the moisture is probably under tension. Suppose also that we begin to freeze this soil. Upon so doing, liquid water under tension is frozen and becomes ice. The question is this, does the ice formed remain under the original tension, or is it separated out from the main body of the liquid soil-moisture to now be under only atmospheric pressure, the standard conditions with respect to pressure of our datum? Much consideration of this has led us to believe that the latter, instead of the former, might well represent the true state of affairs. If this is so, how would the relation between the free energy and freezing-point in the latter case differ from the former given by equation (2)? To answer this we shall take up the derivation of what we here shall call the generalized CLAUSIUS-CLAPEYRON equation.

Generalized treatment of the effect of pressure on the freezing-point, and its application to relatively moist soils--generalized CLAUSIUS-CLAPEYRON equation

Equation (2) gives the change in freezing-point dT caused by a change in hydrostatic pressure dP on water. In its derivation it was assumed that the hydrostatic pressure as well as any changes in its value were exerted uniformly on both the phases (ice and water). Under these conditions, the freezing-point is lowered 0.°00748 C per atmosphere increase of pressure, as shown later. This is only a special case of the following generalized treatment. We shall now consider the case where the hydrostatic pressure exerted on the ice differs from that exerted on the water. We will find, as another special case of this, that the freezing-point of water is lowered 0.°0899 C per atmosphere increase of pressure on the ice alone, the pressure on the water remaining unchanged. This depression is 12 times as great as observed when the pressure is exerted uniformly on both the water and the ice.

To be specific, we derive the following expressions with respect to ice and water, but the results apply equally to any other substance.

Consider Figure (2), in which P_I represents the pressure exerted uniformly on the ice by a piston that is permeable to water-vapor only and P_W represents the pressure exerted uniformly on the water by a piston that is permeable to water-vapor only, P_W and P_I being always so related that there is a common vapor-pressure p throughout. This, of course, means that the three phases are always in equilibrium with each other. The total hydrostatic pressures in the water and in the ice are then

$$P_2 = p + P_W \tag{8}$$

and

$$P_1 = p + P_I \tag{9}$$

respectively, as indicated in the Figure, since the vapor-pressure is acting on both the ice and the water. Let T be the freezing-point of the water under these conditions, that is, the temperature at which all three phases are in equilibrium with each other. In the following discussion, v_1, s_1, f_1, and v_2, s_2, f_2, are the specific volume, the specific entropy, and the specific free energy associated with the ice and liquid phase, respectively.

With the above pressures, we now seek an expression relating the change in freezing-point dT to a change in any one or all of the pressures. Since we have postulated that the phases are to be in equilibrium we have, as a consequence of the thermodynamic properties of free energy

$$f_1 = f_2 \tag{10}$$

This means that when any change occurs in the system, the two free energies must change by an equal amount, namely

$$df_1 = df_2 \tag{11}$$

The free energies of both the water and the ice may be expressed in terms of but two variables of state. Let us for convenience choose these to be the temperature T and the pressure P. We then have

$$df_1 = \left(\frac{\partial f_1}{\partial P_1}\right)dP_1 + \left(\frac{\partial f_1}{\partial T}\right)dT \quad \text{and} \quad df_2 = \left(\frac{\partial f_2}{\partial P_2}\right)dP_2 + \left(\frac{\partial f_2}{\partial T}\right)dT \tag{12}$$

It is a well demonstrated fact in almost any text on thermodynamics that

$$\left(\frac{\partial f}{\partial P}\right) = v \text{ and } \left(\frac{\partial f}{\partial T}\right) = -s \tag{13}$$

so that equations (12) become

$$df_1 = v_1dP_1 - s_1dT \quad \text{and} \quad df_2 = v_2dP_2 - s_2dT \tag{14}$$

Substituting these into equation (11) we have

$$v_1dP_1 - s_1dT = v_2dP_2 - s_2dT \tag{15}$$

where dP_1 and dP_2 are the total changes in pressure on the ice and water, respectively. Unlike the customary assumption of equality in pressures, these two pressures are not in general to be assumed equal to each other. Substituting dP_1 and dP_2 from equations (8) and (9) into equation (15) and dividing through by dT, we have

$$v_1\left(\frac{dp}{dT} + \frac{dP_I}{dT}\right) - s_1 = v_2\left(\frac{dp}{dT} + \frac{dP_W}{dT}\right) - s_2 \tag{16}$$

Rearranging, we have $(v_2dP_W/dT) - (v_1dP_I/dT) + (dp/dT)(v_2 - v_1) = (s_2 - s_1)$. The term $(s_2 - s_1)$ represents the difference in the specific entropies of ice and water at equilibrium. Therefore we may write

$$s_2 - s_1 = (\ell/T) \tag{17}$$

where ℓ is the latent heat of fusion of ice. We have then

$$(v_2dP_W/dT) - (v_1dP_I/dT) + (dp/dT)(v_2 - v_1) = (\ell/T) \tag{18}$$

This equation was first derived by HUDSON (5) through an entirely different line of reasoning. He recognized the following four ways in which the freezing point is changed by changes of pressure.

Case 1--The total change in pressure on the ice is always equal to the total change in pressure on the water. Consequently, $(dp + dP_W) = (dp + dP_I)$. Let the total change equal dP. Equation (18) becomes then

$$(dp + dP_W)/dT = [(dp + dP_I)/dT = (dP/dT) = [\ell/(v_2 - v_1)T] \quad (19)$$

This case is the well-known CLAUSIUS-CLAPEYRON equation given in all thermodynamics texts as is the relation used in deriving equation (2). Substitution of the proper values for the specific volume of water, v_2, and ice, v_1, and the latent heat of fusion ℓ of ice (the latter term is positive) we find that a total increase in pressure dP equal to one atmosphere lowers the freezing-temperature by the amount dT = 0°.00748 C.

Case 2--The pressure on the water remains constant while the pressure on the ice is changed. Consequently, $(dP_W/dT) = 0$ and equation (18) becomes, after dividing through by v_1,

$$(dP_I/dT) = -(\ell/Tv_1) - (dp/dT)[1 - (v_2/v_1)] \quad (20)$$

The first term on the right is many thousand times as large as the last term, as may be seen by substituting the proper values for the different terms, hence it may be neglected, and we have

$$(dP_I/dT) = -(\ell/Tv_1) \quad (21)$$

Substitution of the proper values in the right side of this shows that an increase in pressure, dP_I on the ice alone, equal to one atmosphere, lowers the freezing-temperature by the amount dT = 0°.0899 C, a depression which is 12 times as great as that which is observed in Case 1 when the pressure is exerted uniformly on the water and ice.

Case 3--The pressure on the ice remains constant while the pressure on the water is changed. Consequently, $(dP_I/dT) = 0$, and equation (18) becomes, after dividing through by v_2, $(dP_W/dT) = +(\ell/Tv_2) + (dp/dT)[(v_1/v_2) - 1]$. Neglecting the small second term on the right, as was done in Case 2, we have

$$(dP_W/dT) = +(\ell/Tv_2) \quad (22)$$

Substitution of the proper values in the right side of this equation shows that an increase in pressure dP_W on the water alone, equal to one atmosphere, raises the freezing-temperature by the amount dT = 0°.0824 C. This is in complete contrast to Case 2.

Equation (22) might well describe, for relatively moist soils, the relation between dP_W, the tension in soil-moisture (as measured by a tensiometer for example) and dT, the corresponding freezing-point depression (as determined by the customary BECKMANN method) if the soil-moisture (under a state of tension depending upon the soil-moisture content) is transformed to ice (under atmospheric pressure) upon freezing. This follows because if we have ice and water at equilibrium under atmospheric pressure, then the freezing-point will be 0°C. Now if we change the pressure on the water alone, so that it is under the same tension dP_W as the soil-moisture, then dT, the freezing-point depression of the system, should be given by equation (22). That the change in the freezing-point dT is negative (indicating a freezing-point depression) is seen immediately from equation (22) when it is recalled that dP_W (the tension that must be put on the free water to place it in equilibrium with the soil-moisture) is negative. A comparison of equation (3) with (22) shows that an osmotic pressure dP_0 caused by dissolved material will cause the same freezing-point depression dT as a tension dP_W in the soil-moisture, provided that when the soil-moisture freezes to ice, the ice separates out from the soil-moisture to the higher pressure of one atmosphere.

The total freezing-point depression of any relatively moist normal soil would in this case be the sum of (a) the effect of pressure given by equation (22) and (b) the effect of the osmotic pressure of the dissolved material in the soil-solution given by equation (3). Both expressions have the same form.

SCHOFIELD [6] gives an equation for calculating the freezing-point depression of soil-moisture whose form may be transformed into that of equation (22) when certain suspected typographical errors in his published equation are corrected. He does not give any derivation of his equation

but mentions that the pF-values, calculated from freezing-point depressions, he has plotted in his curve were calculated by means of it.

Case 4--The total changes in pressure on the ice and water are always so related that the freezing-temperature remains constant. Consequently, $dT = 0$ and, upon rearrangement, equation (18) becomes

$$(dP_I + dp)/(dP_W + dp) = d(P_I + p)/d(P_W + p) = (dP_1/dP_2) = (v_2/v_1) \qquad (23)$$

Thus if the changes in pressure on the water and ice are inversely proportional to the specific volumes, the freezing-temperature will not change.

Evidence from freezing-point, vapor-pressure, and tensiometer-measurements indicate the range of hydrostatic pressure occurring in the soil. At high soil-moisture contents the bulk of the liquid is probably under tension, whereas with decrease of moisture-content the pressure increases, becoming very great positively at the low moisture-contents.

Let us illustrate the application of the above four cases by a consideration of several specific examples. Let us first find the freezing-temperature of water, which is under a pressure of ten atmospheres, when upon freezing it is transformed into ice under a pressure of 16 atmospheres. According to Case 1, ice and water are in equilibrium under a uniform pressure of ten atmospheres at $-10(0.00748)^\circ$C. If a pressure of six additional atmospheres be applied to the ice alone, the freezing-temperature will, according to Case 2, fall an additional $6(0.0899)^\circ$C. The resultant freezing-temperature of the system is -0.614°C.

On the other hand, suppose the pressure on the water is 16 atmospheres when its ice is under a pressure of only ten atmospheres. According to Case 1, ice and water are again in equilibrium under a uniform pressure of ten atmospheres at $-10(0.00748)^\circ$C. If now, six additional atmospheres be applied to the water alone, the freezing-temperature will, according to Case 3, rise $6(0.0824)^\circ$C. The final freezing-temperature will now be 0.420°C above zero.

The use of the four cases may be also illustrated by showing that the lowering of the freezing-point of solutions can be considered as the result of osmotic pressure acting as a negative pressure tending to expand the water. At first, this seems strange. It is known that ordinarily a positive pressure lowers the freezing-temperature of water and a negative pressure raises the freezing-temperature; therefore it might seem that solutions should freeze above 0°C rather than below, if the dissolved material produces a tension. As has been pointed out by HUDSON [5] this reasoning is not correct, because the ice which freezes from a solution is under atmospheric pressure, not negative pressure; and only the solution may be properly regarded as being under a negative pressure caused by the dissolved substance. Both the ice and solution are, of course, under atmospheric pressure, but in the case of the solution, the dissolved substance in effect contributes an additional negative pressure to the water. Let us assume that the dissolved material has the same tendency to expand that part of the solvent containing the dissolved material as the molecules of a perfect gas have to expand the volume they occupy. This might be thought of as causing a tension $-P_W$ in the water of the solution tending to pull it apart, and determined by $P_W v = x_2 RT$ where x_2 is the mol fraction of the solute in the solution. (This is recognized to be nothing more than the ideal gas law where R is the gas-constant per gram.) Since this falls under Case 3, let us substitute this expression for $-P_W$ for that in the expression under Case 3 and obtain, after rearrangement, $dT = -(RT^2/\ell)dx_2 = (RT^2/\ell)x_2$, since the origin of dx_2 is measured with respect to that of a pure solvent. It is remarkable that this expression is the same as the well-known expression that VAN'T HOFF obtained for the freezing-point depression, dT, produced by the addition of an amount of solute dx_2. From the agreement of these two expressions of the molecular depression of the freezing-temperatures, we must conclude that solutions may be regarded as being under a negative pressure, comparable with a positive mechanical tension, this negative pressure being caused by the dissolved substance and being numerically identical with the osmotic pressure of the solution.

Let us consider another illustration. As pointed out under Case 4, it is possible to apply pressure to the ice and water in such a way as not to change the freezing-point of the water. We had $(dP_1/dP_2) = (v_2/v_1)$. The specific volume of ice is $v_2 = 1.0909$, and of water is $v_1 = 1.0001$ cc per gram, respectively. Thus $(dP_1/dP_2) = 1.09$, so that the freezing-temperature of the water will always remain the same no matter what pressure is applied to it so long as the pressure applied to it is nine per cent greater than that simultaneously applied to the ice.

Finally, it seems that freezing according to Case 3 might occur both in the freezing of soil-moisture in the field during winter and in the soil-sample in the BECKMANN method of freezing-point measurements at relatively high soil-moisture contents, already discussed. If the ice (freezing out from the relatively moist soil) separates out from the soil-moisture to a pressure of one atmosphere, then Case 3 occurs. Let us consider the following hypothetical case. Suppose in a soil-cavity some distance above a water-table, we have an isolated particle of ice; and suppose also that below this cavity and extending down to the water-table are capillary columns of water. Since the water in capillaries is under tension, it will at 0°C have a lower vapor-pressure than the particle of ice. Consequently, the moisture-system in the cavity will not be at equilibrium at that temperature and the ice will distill over to the water in the capillaries. The temperature of equilibrium may be calculated as follows: The water in the capillaries leading up to the cavity is under a tension that is less than atmospheric by an amount determined by the height of the capillaries above the water-table. If for the sake of our present argument, we assume that the water-table is 76 × 13.6 cm below the cavity and that all the soil-capillaries are small enough to raise the water this high, then the hydrostatic pressure in the water at the upper end of the soil-capillaries having their termini in the cavity is -76 × 13.6 grams, or -1 atmosphere. At 0°C, if the water in the soil-capillaries were not under tension, it would be in equilibrium with the isolated particle of ice in the cavity and would freeze at 0°C; however, in our present case, we must consider the pressure on the particle of ice in the cavity as remaining constant whereas the pressure on the capillary water adjacent to the cavity has been decreased by one atmosphere. Thus, according to Case 3, the ice-particle-soil-moisture system in the cavity will be in equilibrium at -0.0824 C, at which temperature that part of the soil-moisture adjacent to the cavity which is under a tension of one atmosphere will begin to freeze. That is, the freezing-point of the soil-moisture which is under a tension of one atmosphere is in the present case -0.0824 C since the particle of ice is isolated from the water and not +0.00748 C as might at first have been expected if Case 1 had inadvertently been applied under the assumption that the ice was attached to the water and both under the same pressure. In general, if the soil-capillaries are all small enough and the cavity containing the isolated particle of ice is h cm above the water-table, the freezing-temperature of the moisture adjacent to the soil-cavity is h(0.0824/76 × 13.6) degrees below 0°C.

Movement of soil-moisture in relation to freezing phenomena in soils

From the discussion in connection with Figure 1, it is clear that if soil-moisture is subjected to a temperature lower than its freezing-point, a portion of the moisture freezes. It is clear also from the explanation above, that the portion of water frozen is that which is farthest from the surface of the soil-particles and hence it is that part which, in the liquid state, is most mobile. This fact coupled with the consideration that after freezing has taken place much of the space formerly occupied by fluid is then occupied by solid requiring slightly more volume, makes it evident that the motion of water under a given force through a frozen soil is markedly curtailed. Two types of water-movement related to the freezing of soils call for consideration.

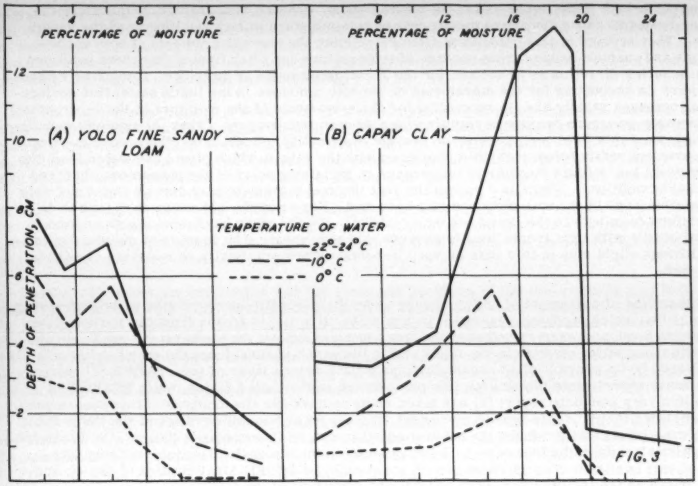
One is the downward motion of water under gravitational force. This has definite practical importance in relation to soil-erosion and runoff from watersheds. The literature reveals very few measurements relating to this phenomenon either as observations in the field or as experiments in the laboratory. Some tests in the laboratory have indicated that the depth of penetration of water into frozen soil is slight. Tests were conducted on Yolo fine sandy loam having a moisture-equivalent of 15.7, permanent wilting-percentage of 7.9, and a sticky point of 8.5, and on Capay clay having a moisture-equivalent of 28.7, permanent wilting-percentage of 13.7, and a sticky point of 23.1. The soils at varying moisture-contents were placed in glass tubes and frozen at -10°C. Figure (3) shows the depth of penetration of water as a function of moisture-content of the soil. The curves show maxima in the depth of penetration at definite moisture-contents which suggest that penetration is related to structure. This is substantiated in Figure 4 where the average depth of penetration for both soils, with the applied water at approximately 20°C, is shown as a function of the ratio of the moisture-content at the sticky point. This seems to indicate that the maximum depth of penetration is closely related to the sticky point.

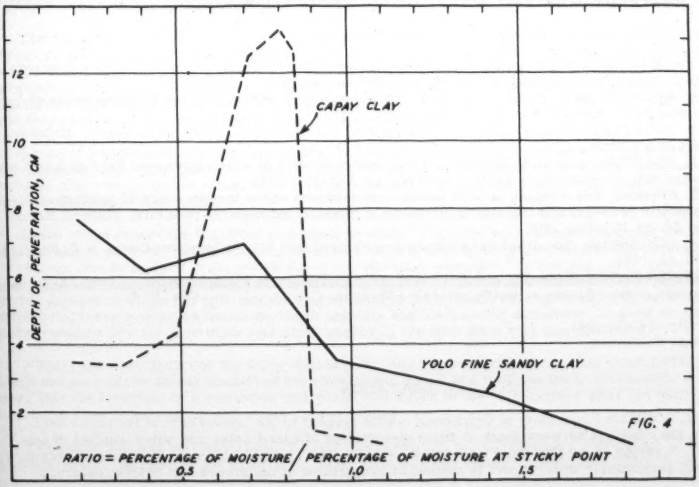
It is clear from Figure 3 that very little water entered the frozen soils. If similar depths of penetration can be expected in the field when rain falls on a frozen soil, practically the entire precipitation may be regarded as potential runoff. It is well known in cold climates with high rainfalls that the soil may be quite dry, in the spring, a short distance below the soil-surface because it has been sealed off by a layer of frozen moisture.

As the water penetrates into the soil, the heat-content of the downward moving water front is decreased until it freezes. Where it freezes a layer of ice is formed markedly decreasing any

further downward movement of water. Above this layer of ice, the soil is practically saturated with water which makes it susceptible to erosion.

Another type of motion which plays an important role in relation to frozen soils is the movement of water under thermal gradients. This motion is probably very slight through the frozen





soil but is very closely associated with some soil-freezing phenomena. A considerable number of investigations in the laboratory of this problem have been made, but only a few measurements have been reported on field-work except in connection with frost-heaving. EDLEFSEN and BODMAN [4], although working at higher temperatures than 0°C, made some observations which are of interest in this connection. They found that under the conditions of their measurements, the temperature-gradients during the winter in the top ten feet of soil were such as to tend to cause water to move upwards both in the vapor and in the liquid phases, whereas temperature-gradients in the summer tended to cause downward movements of soil-moisture in both the liquid and the vapor-phases. They arrived at this conclusion after calculating the average gradients of both vapor-pressure and surface-tension from records of temperature and after finding that these produced forces in such a direction as to account for the actual movements of moisture. It must be remembered here (in accounting for the movements of the soil-moisture in the liquid state) that surface-tension increases rapidly and (in accounting for the movements of the moisture in the vapor-state) that the vapor-pressure decreases rapidly with a drop in temperature. They [4] studied the moisture-movement in a field-plot, covered to prevent evaporation, on which no plants were growing. This movement, while being negligible compared with the rate at which plants use water from the soil, no doubt has definite theoretical importance in explaining some of the phenomena observed under field-conditions. There is a possibility that thermal movement may play an important role in the maintenance of the soil-moisture of a seed-bed. For example, hot sunny days tend to drive the moisture down both in the liquid and vapor-phases. On the other hand, cool nights and mornings, especially with light frosts tend to reverse this movement. The quantity of moisture-movement although slight may in this case be very important since practically no moisture is used in a seed-bed.

Another type of movement of soil-moisture under field-conditions correlated with the freezing of soils is that which produces heaving of frozen soils. If a soil is frozen from the surface down to a definite depth and warmer unfrozen moisture remains below, the temperature-gradients are such as to move water up (both in the liquid and in the vapor-phases) from the moist unfrozen soil to the frozen layer where it often accumulates as a thick frozen layer of ice. TABER [7] has carried on many experiments illustrating this phenomenon in the United States, while BESKOW of Sweden in a very complete report [1] has given many remarkable illustrations of this phenomenon. They concluded that it is this type of movement, causing an accumulation of ice at the lower limit of the frozen layer, that produces the heaving and it is not, as is sometimes thought, the expansion of the water already in the frozen soil. By varying the intensity of the thermal gradients they found not only one layer of ice formed but, in some cases, a definite stratification of the ice and soil produced as the temperature-wave progressed downward in the soil.

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DISCUSSION

G. B. BODMAN (University of California)--With respect to the second part of the paper dealing with the relations between depth of water-penetration of added water and water-content of frozen soil, it seems to me that quite a lot might be said. But I should like more information than is provided, particularly with respect to method of preparation of moistened soil before freezing,

method of packing in tubes, method of freezing, average apparent density of soil in each tube--and no doubt dilatometer and other data would be helpful. But as it is I could do no more than speculate about the most interesting parts of the phenomena.

Reasoning with respect to a porous system consisting of an ideal, coarse, monodisperse set of spherical particles, suggests to me that the Yolo fine sandy loam has behaved in a predictable fashion. The Capay clay, on the other hand, seems to have behaved unexpectedly, which suggests that some major changes may have been induced in the structural state of this soil either during the wetting or the packing process, or both. By this I mean structural changes which would not have come about could the soil have been brought to different moisture-contents without manipulation either during, or subsequent to, moistening.

At the moisture-equivalent of both soils (and also, I suspect, at those moisture-contents corresponding to their respective sticky points), the volume of gaseous phase per unit-volume of soil including all phases, will be greater in the coarser than in the finer soils. From this it would seem that the curves for the finer-textured soil should have followed a similar trend to, but should have attained lower magnitudes than, those of the coarser soil (Figure 3). But this does not happen for the Capay until moisture-contents in excess of 14 per cent are reached and I wonder if the differences in behavior may not have been influenced by packing differences. Supposing, for example, that the various desired water-contents had been obtained by diffusion of water-vapor into the soil-column already packed in the tubes, rather than by first wetting and then packing, would the same results have been obtained?

Further, it seems not impossible that the sizes and positions of the ice-crystals may have played an important role--for example, at about 16 to 18 per cent water-content it might be that the resultant type of packing in the tubes produced a unique, open arrangement of the soil-particles after the freezing, which arrangement, however, was not independent of the packing process. I do not feel very greatly moved by the graphical simplification which apparently comes about as the result of dividing water-content percentage by corresponding sticky-point per cent. The same sort of thing would have happened had the divisor been the moisture-equivalent per cent.

E. A. COLMAN (United States Department of Agriculture Forest Service)--Theoretical presentations of this kind are of great value in establishing a solid foundation upon which can be based the consideration of practical problems. This paper and several other reports of the Committee on Physics of Soil-Moisture are of importance because they have clarified the modern energy-concepts of soil-water relationships.

The report would be strengthened if the definitions of some of the components of the total free energy of the moisture were given in more detail. Thus Δf_p is considered to represent the free energy-component due to hydrostatic pressures of the soil-moisture. The text states that this pressure is "in excess of that ..... in free, pure water under one atmosphere pressure." Unless I misunderstand the use of Δf_p, hydrostatic pressures can also be negative in the case of soil-moistures below those corresponding to pore-space saturation.

Again, if I understand the meaning of Δf_F, it includes the attractive forces existing between the soil-particles and water-particles, due to their masses. I have not encountered this component of the total free energy before in the literature of soils and feel that some further discussion might be advantageous in introducing it.

Later in the report the following statement is made: "At high soil-moisture contents the bulk of the liquid is probably under tension; whereas with decrease of moisture-content the pressure increases, becoming very great positively at low moisture-contents." Freezing-point, vapor-pressure, and tensiometer-measurements actually indicate negative pressures (relative to atmospheric pressure) within the soil-moisture at moistures lower than that represented by pore-space saturation, these pressures becoming more negative with decreasing moisture. I cannot reconcile measurements which I have made and which appear in the literature with this statement.

Finally the description of the water-penetration experiment could be clarified considerably. I was not sure of the actual conduct of the experiment until I had read the whole discussion. I believe that the insertion of a statement that water was added to the soil-surface after the initial water had been frozen in the soil would aid the reader.

The authors are to be commended on their interpretation of soil-moisture phenomena in terms of fundamental thermodynamic principles. This approach has already proved invaluable in other

fields of science and will do much toward raising the standards of research and increasing our understanding in the field of plant-soil-water relationships.

C. A. HOGENTOGLER and E. S. BARBER (Public Roads Administration, Federal Works Agency)--Damage due to frost which is the most spectacular effect of temperature-variation, has been described repeatedly. For the present purpose, it suffices to say that ice-lenses are involved and that two theories have been advanced to explain their formation.

One theory was advanced by STEPHEN TABER [Freezing and thawing of soils as factors in the destruction of road pavements, Public Roads, August, 1930] and the other by A. C. BENKELMAN and F. R. OLMSTEAD [A new theory of frost heaving, Proc. Eleventh Ann. Meeting, Highway Res. Board, 1931, Part I, page 152].

The requirements for the growth of ice-lenses according to TABER'S theory are: (1) Soil with detrimental capillary properties; (2) the presence of pore-water (probably in film-phase) in the soil, which has the property of remaining unfrozen at temperatures far below the freezing-temperatures of water in bulk (such moisture, it is indicated, may remain unfrozen at temperatures as low as - 70°C); (3) the occurrence of more or less continuous periods of normal freezing air-temperatures, that is, below 32°F or 0°C.

According to BENKELMAN and OLMSTEAD, ice-lenses may be formed under conditions as follows: (1) In relatively permeable soil without respect to its capillarity; (2) at complete saturation of the soil with pore-water which can be frozen at the freezing-temperatures of free water in bulk; (3) with alternate fluctuations of normal freezing- and thawing-temperatures. Also, the resulting damage due to frost is of two kinds. In one kind of damage, moisture drawn from the water-table below or other unfrozen source migrates towards the surface of the soil during freezing weather and forms the ice-layers which produce considerable heave of road-surface. The second type of damage consists principally of an abrupt drop in the stability of soils during thaws. The road-surfaces and pavements may not heave appreciably and are likely to remain undamaged as long as the undersoil remains frozen. Under conditions of accelerated freezing in the laboratory, it has been found possible to produce ice-lenses in every type of soil from the permeable sands to the colloidal clays. However, this has not been found to be the case in the field. Under the normal climatic conditions of continental United States, it has not been found that plastic clay-soils have been seriously affected by frost; and from investigations in Denmark and Sweden, it can be concluded that cohesionless soils, with a capillary rise not exceeding about three feet are not likely to prove troublesome due to frost. (Actually GUNNAR BESKOW gives a value of h less than 40 inches for soils which are not subject to frost-heaving. He states further, however, "when the figures exceed these limits, the soil is usually classed as frost-heaving, although those near the limits in reality belong to a rather complicated border-zone" [Prevention of detrimental frost heave in Sweden, Proc. Eighteenth Ann. Meeting, Highway Res. Board, 1938, Part II, page 366].)

It is the relatively cohesionless silt-soils which have proven most troublesome, that is, the soils which, according to previous discussion, have values of capillary rise ranging from about h = 3 to at least 30 feet. Observations of frost in such soils indicate that both of the theories mentioned above are valid. In some cases the water productive of damage undoubtedly rises from the water-table due entirely to the capillarity of the soil. For damage to occur in other cases, it seems that the soil must first be completely saturated in much the same manner that a pump is primed before water can be raised from the well beneath.

ROBERT E. HORTON (Consulting Hydraulic Engineer)--I have long advocated more general use and application of fundamental physical laws and principles in connection with hydrologic problems. This report is directed along this line and it would seem to me appropriate that further study along the same line might well form a basis for a report of the Committee next year, giving, where possible, quantitative applications of the formulas and results appearing in this year's report.

It is true that infiltration-capacity of soil frozen when moist is in general relatively low except for sandy soils, but it is nevertheless of the utmost practical importance, especially where such a soil underlies a heavy snow-cover. The prolonged duration of snow-melt as compared with the duration of rain provides opportunity for infiltration such that, even with a low infiltration-capacity, as much water may enter the soil as would enter the soil during an entire summer's rain. Values of infiltration-capacity of frozen soils of the order of 0.01 to 0.05 inch per hour have been obtained where the infiltration-capacity of the same soil would be as many tenths inch per hour under summer conditions. An infiltration-capacity of 0.05 inch per hour will, however, permit 12.0 inches of water to enter the soil during a ten-day period of melting of a snow-cover. If the infiltration-capacity is 0.01 inch per hour, only 2.4 inches of water would enter the soil but this may still be highly significant in relation to crop-growth during the subsequent summer. While these values

appear small, it is evident from the example given that it may be of very great practical importance to know whether the infiltration-capacity of frozen soil is of the order of 0.01 inch per hour or 0.05 inch per hour.

There has been much discussion, and not always agreement, on the question whether upward flow of heat from below the frost-line aids materially in removal of frost. There seems to be some rather convincing evidence that it does.

The report of the Committee suggests another possibility and that is that increased concentration of the soil-solution proceeding downward at the time the soil freezes, with consequent lowering of the freezing-point as depth below soil-surface increases, may be an important factor. To illustrate--water in the surface-layer of the soil when it freezes may recently have entered and contain no appreciable mineral matter in solution. Soil-moisture at three-foot depth may already have been in the soil for some time and acquired an appreciable concentration. Furthermore, freezing at three-foot depth will occur considerably later than at the surface. In the meantime the moisture-concentration at this depth will increase, with the result that the freezing-point at three-foot depth, and later on the melting-point when the frost goes out of the ground, will be considerably lower than close to the surface. The temperature-profile in the soil in the early spring may therefore be such as to remove frost from the soil at three-foot depth before there is appreciable thawing at the surface. This point may or may not be important but it seems to me that it should be cleared up. Incidentally the Soil Conservation Service has, I believe, maintained records of soil-moisture, depth and march of soil-moisture penetration at some of its experiment stations. These data could presumably be obtained from the Research Division of the Soil Conservation Service and might prove useful in further studies of this question as supplying data for application of the physical and thermodynamic laws to the problem.

R. A. PENDLETON (Oregon State College)--It would have been worth-while discussing in further detail the upward movement of soil-moisture in soil during cool nights when the surface of the soil freezes for one-half inch or more. This is an important feature in some localities, particularly with respect to cultivation and control of weeds. Soils that are dry enough to cultivate in afternoons may be too wet all the following forenoon due to freezing of the surface. I would like to see some calculations of how much moisture is brought up this way.

L. A. RICHARDS (United States Department of Agriculture, Bureau of Plant Industry)--I am happy to see continued interest in the thermodynamic function free energy as a quantity for expressing the condition of soil-moisture. It is unfortunate that convenient and accurate means for its direct measurement seem not now to be available for use in the plant-growth-moisture range. Some effort is being made at this laboratory to develop a vapor-pressure method, but it is too early to predict whether our work will meet with success.

It is pointed out in the paper that the results from freezing-point-depression measurements appear to depend somewhat upon the experimental procedure used. As improvements in freezing-point-measuring methods are made [see 1 of "References" at end of this discussion], it is likely that the correct use of the theory in calculating free-energy values will become easier.

In Figure 1, freezing-point-depression values are given for Aiken soil having a moisture-equivalent of 31.5 per cent. By means of our pressure-membrane apparatus [2] we have recently obtained water-sorption data on a sample of Aiken soil which I believe is from the same source as that of Figure 1 and has a moisture-equivalent of 31.6 per cent.

Table 1--Comparison of measured freezing-point-depression values with values calculated from pressure-membrane-sorption-curve data

Air-extraction pressure (1)	Equilibrium soil-moisture (2)	ΔT from Figure 1 (3)	ΔT calculated (4)
atm.	pct	°C	°C
1	28.6	0.25	0.0824
3	25.4	0.43	0.247
5	23.9	0.58	0.412
10	22.0	0.80	0.824
15	21.2	0.94	1.236

The first column in Table 1 gives the air-pressure in the soil-chamber of the apparatus and the second column gives the moisture-percentage the soil retained at equilibrium with the permeable cellophane wall of the chamber. In the third column are given the freezing-point-depression values corresponding to these moisture-contents as taken from the curve in Figure 1. In the fourth column are given freezing-point-depression values calculated at the rate of 0°.0824 C per atmosphere pressure of the gas in the extraction chamber. Curves plotted from columns (3) and (4) have the same general form but cross each other at a moisture-content of 22.5 per cent and 0°.75 C depression.

If the pressure-membrane apparatus deals only with the adsorptive force-field component of the free energy then we might expect a constant difference in the two curves due to the osmotic concentration of the soil-solution. It is possible the moisture retaining properties of the two soils were actually quite different in spite of the close correspondence of their moisture-equivalent values.

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C. S. SLATER (United States Department of Agriculture, Soil Conservation Service)--What bearing could the paper have on the determination of wilting-points by the dilatometer-method, which essentially substitutes freezing-point measurements for vapor-pressure measurements, and assumes that the wilting-point (if the idiosyncrasies of plant-soil relationships are neglected) represents a rather definite point on the vapor-pressure curve?

Can you make the relationship of sticky point to water-penetration logical rather than empirical?

When the winter cold was sufficiently intense and the snow-cover sufficiently thin, soils froze in New York under every type of cover. Thawing out was a different matter, and a thick matted cover of bluegrass apparently prevented the Sun's rays from getting at the frozen soil below. Soil under bluegrass remained frozen sometimes when soil under more brushy cover, standing soybeans or buckwheat, thawed out. This resulted in larger relative runoffs from bluegrass. I have wondered if the point had some bearing on the choice of forest-cover versus grass for the control of flood-runoffs in the spring flood-areas.

BYRON T. SHAW (The Ohio State University)--The terms "high" and "low" in the statement "At high soil-moisture contents the bulk of the liquid is probably under tension, whereas with decrease of moisture-content the pressure increases, becoming very great positively at the low moisture-contents," are rather unsatisfactory. In the discussion it is shown that the hydrostatic pressure decreases with increasing height in the neighborhood of 1000 cm above the water-table. Just where does the change occur to increasing pressures with decreasing moisture-content, or are we to infer that the moisture in a soil not connected to a water-table is radically different from the moisture in a soil so connected? Does the free energy due to the adsorptive field Δf_F decrease so rapidly with decreasing moisture as to keep the total free energy of the system decreasing even though the hydrostatic pressure is increasing with an approach to the surface of the particle?

I doubt if soils under natural conditions in the field would show such pronounced maxima in the curves relating depth of penetration to moisture-percentage as the curves in Figure 3 suggest. Volume-weights of the soils used were not given but it is very probable that they were much lower at the points of maximum penetration than at either lower or higher moisture-contents. Dry or wet soils can be compacted more easily than soils of intermediate moisture-contents. In the field the volume-weights would change much less with changes in moisture than would be true for the artificially packed systems shown in Figure 3. Nevertheless it would be expected, as the authors point out, that penetration is related to soil-porosity. Depth of penetration should increase with an increase in the large or so-called "non-capillary" pores. This is probably the reason for the high maxima in the curves for Capay clay. In the artificially packed systems it would be expected that there would be a relatively high proportion of large pores in the soil packed at moisture-contents slightly below the sticky point. In the fine sandy loam on the other hand little change in pore-size distribution would be expected as a result of packing at different moisture-contents. If no

change in pore-size distribution occurred I would expect that depth of penetration would decrease uniformly with increasing moisture.

We are obtaining data in our present studies that will support the contention that moisture moves downward from the surface during the day and upward during the night as a result of temperature-gradients.

F. J. VEIHMEYER (University of California)--The relation of the depth of penetration of water as a function of moisture-content of the soil when the soil is frozen at a temperature of -10°C raises the question of the relation of the structure of the frozen soil to the depth of penetration before the applied water freezes. The importance of the effect of soil-structure on the infiltration-capacity has been stressed by students of hydrology. While tests were made on only two soils, they will be surprising to those who would assume that clay-soil always would be less permeable than the sandy ones. The Yolo fine sandy loam is a much more permeable soil than the Capay clay when in place in the field. In these tests, however, when the soils were placed in small glass tubes and frozen, the penetration of water into the clays, except at very low moisture-contents, is equal to or better, in some cases, than into the sandy loam.

While the total porosity of the two soils might be the same when in place in the field [Report of the Committee on Physics of Soil-Moisture, Trans. Amer. Geophys. Union, Part 2, pages 426-432, 1935], the size of the individual pores in the clay are smaller than in the sandy loam and the configuration of the pores might also be different. Hence the infiltration-rate is usually lower in the former soil than in the latter one. Generally the porosity of clays when packed in tubes is greater than sands, a condition which probably existed in the reported tests, although no data are presented to indicate the structural differences which might have existed in the two soils. Actually, the clay-soil particles may have been, in a large part, in the form of relatively large pellets and the soil acted like a sand. This raises the question of the applicability of the results of the tests to field-conditions in regard to the effect of soil-types upon infiltration of water into frozen soils. Certainly the structural condition of the soils in the tubes might be markedly different than that of the same soil when in place in the field or upon which plants are growing.

Another point to consider is that moist soils at high elevations on watersheds where the penetration of water is said to be of prime importance in the control of floods are primary soils while those tested were recent alluvial. The former are generally highly permeable soils--at least much more so than most alluvial soils. In either case, however, it is clear that when frozen, penetration is extremely slight, and thus the soil cannot serve as a reservoir for infiltrating water and during periods of high precipitation, runoff must take place.

The fact that two maxima in the penetration-rate occur at a certain moisture-content of the soil when water at different temperatures was applied is more striking in the case of the clay than with the sandy soil. I believe the slight rise in the curve at about six per cent in the Yolo soil probably is not significant. Although the maxima of the increase in rate of penetration at moisture-contents of from about 14 to 18 per cent in the Capay soil are large enough to suggest favorable structural conditions for the penetration of water in this region, it is interesting to note that the maximum rate of penetration occurs at a moisture-content well below the moisture-equivalent and in the region at about which the minimum volume on compaction occurs--in other words, where there would be the smallest porosity.

My suggestion that the results may not be strictly applicable to field-conditions does not in any way deprecate the value of contributions made in the paper to a clear understanding of penetration of water into frozen soils, but is given solely as a matter of caution, especially in view of the results obtained in studies of movement of water through columns of soils carried on at Davis a number of years ago in which the rates were shown to be definitely affected by the cross-sectional area of the tubes used in the tests.

Since the question of changes in structure due to manipulation in mixing the soils to various moisture-contents before they are placed in the tube naturally arises, it would be interesting to try a similar set of experiments to test this point. The soils could be placed in the containers in a dry condition, all saturated with water and allowed to drain, after which plants could be grown in the soil and allowed to dry the soil out to various moisture-conditions before the soil was frozen. Under these conditions, a more uniform structure and density in all samples would be obtained and yet they could be reduced to the various moisture-conditions before the freezing was done. I suspect that under such conditions, which would probably more nearly represent the condition existing in the field, the maximum shown for the Capay clay would not be so pronounced.

N. E. EDLEFSEN (University of California)--Several of those commenting on the paper have mentioned that the conditions in connection with the experiments on the entry of water into frozen soils were not explained sufficiently in detail. The authors deliberately left this explanation out because of lack of adequate space available. A number raised the question as to the importance of structural changes occurring in the soil while being mixed to various moisture-contents preparatory to the freezing-experiment and believe that this, in part, accounts for the maxima observed in the penetration of water as a function of moisture-contents in the frozen soils. This is no doubt the case and was the reason why the results were related by the authors to the sticky point. Some thought it doubtful that such a maximum would be experienced under field-conditions while others thought that it would probably, even if present, be greatly minimized. It was hoped that some definite information on this point would be forthcoming from some of those to whom the paper was sent, but apparently there is a dearth of such information which emphasizes the necessity of obtaining some direct evidence. VEIHMEYER suggests an experiment to minimize the effect of structure by using plants to dry out the soil to various moisture-contents in place of mixing them to the desired moisture-contents.

HORTON suggests that even though the rate of entry of water into frozen soils is small, the time available for such motion is rather long during the winter months and therefore he believes that the amount of water which passes into the frozen soil during these months may be quite appreciable.

COLEMAN, SLATER, and SHAW raise questions on the interpretation of some of the theoretical discussion in the article. COLEMAN raises the question as to the sign of Δf_p. This, of course, can be positive or negative since we used one atmosphere as our datum. He states that "Freezing-point, vapor-pressure, and tensiometer-measurements actually indicate negative pressures (relative to atmospheric pressure) within the soil-moisture at moistures lower than that represented by pore-space saturation, these pressures becoming more negative with decreasing moisture," and further states that he cannot reconcile measurements which he has made and which appear in the literature, with our statement in the paper that at lower moisture-contents the hydrostatic pressure in the soil may become very great. This, I think, is a concept which is very often misunderstood. Let us consider the vapor-pressure first. The vapor-pressure may be reduced if the air-water interface is concave to the air. Under these conditions, the water which is under the surface is under a pressure less than atmospheric. However, we must remember that the vapor-pressure can also be reduced in another way, namely, if the water is in an adsorptive field. Under this condition, the hydrostatic pressure may be very great and the vapor-pressure may be very much reduced over that of free water. We must keep in mind that simply because the water in a tensiometer is under what we might call tension, this does not necessarily mean that all of the water in the soil is under tension for the reasons mentioned above. It means only that the free energy of the water in the tensiometer is the same as that of water in the soil. As for freezing-point data, we must remember also that the free energy of soil-moisture is not necessarily determined by its freezing-point unless we know the factors that determine the depression. For example, assume that water under tension is in equilibrium with a solution through a semipermeable membrane--that is, the free energy of the water under tension is in equilibrium with the water in the solution. This means that their vapor-pressures are equal. If the temperature of such a system, however, is lowered, the pure water under tension will freeze at a temperature higher than zero, whereas the solution will freeze at a temperature lower than zero.

COLEMAN also felt that Δf_p deserved more discussion since readers are probably less familiar with that term than some of the others. As we have used this term, it includes all components of the free energy due to the position of the water in any field affecting it. These fields may be electrical, mechanical, adsorptive, or gravitational. The latter two, of course, are the important ones in soil-moisture studies, but in any treatment of thermodynamics, this term must be included.

SLATER wonders just how the theoretical discussion applies to dilatometer-measurements for the determination of free energy at the permanent wilting-percentage. Although not explained in the paper because of lack of space, we do not believe that an adequate explanation of the thermodynamic interpretation of dilatometer-measurements has been published. Two of the authors have developed a theory which we think is sufficiently adequate for a reasonable thermodynamic interpretation of dilatometer-measurements. This paper will be published in the near future.

SHAW raises the question as to the relative effects of free energy due to pressure and the free energy due to fields, particularly adsorptive fields, in the soil-moisture. In this connection, it should be pointed out that for high moisture-contents at least, the water is under an air-water interface concave to the air and therefore the water immediately under this interface is under a

pressure less than atmospheric. As the surface of the soil-particles is approached, however, the pressure due to the field-forces becomes greater. Thus the curved air-water interface and the adsorptive field-forces work in opposite directions insofar as their effect on pressure is concerned. At a given moisture-content we may move in the liquid phase from a point just beneath the air-water interface where the pressure is less than atmospheric to one of great positive pressure near the surface of the soil-particle and yet the free energy would be constant throughout all points of the path. If the soil-moisture is decreased, the summation of the free energy caused by these two factors is, of course, decreased.

RICHARDS made an interesting calculation using the curve presented in the paper showing the freezing-point as a function of moisture-content using the BECKMANN technique on Aiken clay loam. He selected the ΔT (freezing-point depression) for definite moisture-contents. He had previously run tests using his pressure-membrane extraction apparatus and determined the moisture-content for the different pressures which he had to apply to force water out of the soil. This means that by increasing the hydrostatic pressure, he was able to raise the free energy of the water in the soil, with which he worked, to zero and probably slightly above before the water was forced out through the membrane. The positive pressures which he applied might be assumed to be of the same magnitude as the negative pressures existing in the moisture by virtue of the fact that it was under a curved air-water interface. Assuming that case (3) of our theoretical discussion applied, he calculated what the ΔT (freezing-point depression) would be. The curve representing his calculated values crosses the experimental values as given in the paper. The fact that the two are of the same order of magnitude is very interesting. In this connection, it is worth-while pointing out that freezing-point depressions in the neighborhood of the permanent wilting-percentage are extremely difficult to make accurately. Also, at these moisture-contents, the concentration of the salt when crystallization starts is no doubt quite appreciable. For this reason, one might expect the freezing-point depression as observed from experiment to be higher than that calculated by RICHARDS' method. The reverse, however, is the case.

REPORT OF ADVISORY COMMITTEE ON SOIL-CONSERVATION RESEARCH, 1941-42

Robert E. Horton, Chairman

Under the provisions of the act creating the National Research Council, a Government bureau or agency can request advice or the appointment of an advisory committee on scientific research. Arrangements for the appointment of this Committee were made through Dr. W. C. LOWDERMILK, then Chief, Division of Research, Soil Conservation Service, at the dinner meeting of the Section of Hydrology, in 1937. The membership of the Committee has not changed during the past year and consists of J. E. CHURCH, W. W. HORNER, A. F. MEYER, C. M. SAVILLE, L. K. SHERMAN, SAMUEL SHULITS, ROY N. TOWL, F. J. VEIHMEYER, and ROBERT E. HORTON (Chairman).

During the past year the activities of the Committee have been, as heretofore, carried out chiefly by correspondence and also through an Executive Sub-Committee consisting of Messrs. HORNER, SHERMAN, and HORTON (Chairman). The members of the Executive Sub-Committee happen to be so situated that they visit Washington from time to time; they keep in touch with research-activities of the Soil Conservation Service. In addition, field-trips are made by members of the Executive Sub-Committee from time to time as opportunity offers. During the past year such field-inspections of research-work have been made at stations in Missouri, Texas, Idaho, Washington, Pennsylvania, and Michigan.

The purposes of the Committee may be considered as twofold: (1) From the viewpoint of the Section of Hydrology of the American Geophysical Union, to aid in securing from the research work of the Soil Conservation Service the greatest possible contributions and advancement to scientific hydrology; (2) to give the Department of Agriculture, particularly the Soil Conservation Service, the benefit in its research work of the advice of hydrologists wholly outside the Department of Agriculture, both in planning and executing researches and in publishing and analyzing the results.

The Committee believes that constructive criticism, especially when it comes from those not directly connected with a specific research, is among the most helpful services such a Committee can offer.

The research-work of the Soil Conservation Service, in addition to hydrology, serves several purposes: (1) It may provide important direct contributions to scientific hydrology; (2) it may

provide a better, more complete, and sound basis of knowledge of the interrelations of water to soils and plants; (3) it may provide much needed data for use in connection with upland flood-control, land-use betterment, erosion-prevention, and increased crop-production through improved agricultural practice. Some of these practices, such as reduction of crop-damage by flooding of agricultural lands or, in other words, upland flood-control, are relatively new and precedents and antecedents such as exist, for example, in relation to flood-control through reservoirs or channel-structures, are almost wholly wanting.

It so happens that the work of the Department of Agriculture in relation to upland flood-control and soil-conservation, and the hydrologic research in relation thereto, were established simultaneously. As a result of the conditions described there has arisen an urgent need for the results of hydrologic researches of the Soil Conservation Service to be made available and reduced to a usable basis. Similarly, the advancement in hydrologic theory, methods, and practice during the past ten years has extended to other Government agencies and to hydraulic engineering practice outside of Government agencies, creating an additional demand for the results of hydrologic research. Fortunately, perhaps, these demands for practical working data derived from hydrologic research in relation to soil conservation and agriculture arise along lines where scientific hydrology is itself least advanced, and so offer an incentive for active promotion of the science of hydrology.

To illustrate this, the following examples are given of problems in connection with upland flood-control for which the results of hydrologic research are most urgently needed.

(1) Better determination of the laws of sheet-erosion and of sedimentation, and of transporting power of sheet-flow or surface-runoff before it reaches stream-channels. Hitherto much more attention has been devoted to transport of sediment in stream-channels than in overland-flow, although a large part of the sediment transported by streams is derived not from the channels themselves but from the tributary upland drainage-areas. Research in this connection may be of wide applicability. It has unquestionably an important bearing on the physiographic origin and development of streams and their drainage-basins.

(2) Channel- or valley-storage and the phenomena accompanying the passage of a flood through a system of stream-channels. This again, while of the utmost practical importance, is a question of fundamental significance in relation to scientific hydrology; and one in which great advancement can be made. From the practical viewpoint it appears that, in many cases, so-called flood-routing becomes necessary, both in connection with channel flood-control and upland flood-control, where adequate stream-gaging records are unavailable. The problem can be solved in such cases if data regarding valley- or channel-storage characteristics and flood-crest reduction as a result of the operation of valley-storage are available.

(3) The hydrology of winter runoff, in particular (a) infiltration through frozen soils, (b) transmission-capacity of a snow-layer and the law of overland or sheet-flow through melting snow, (c) the snow-melting constant and its relationship to insolation and radiation. Here again is a problem of vital and practical importance and of immediate necessity in connection with upland flood-control problems; and one which affords an opportunity for a real advance in scientific hydrology. Practically, the engineer working with winter flood-problems must determine snow-melting rates largely from temperature-records because other data are not, nor are likely to become, generally available to a sufficient degree. To do this to best advantage, however, requires a much better knowledge than at present exists of the relationships between air-temperature and the fundamental causes operative in producing the melting of snow.

Knowledge of sheet flow, overland-flow and infiltration-capacity unquestionably has been greatly advanced through the development of the sprinkled-plat infiltrometer on a practicable basis by the Soil Conservation Service, following somewhat the lines of pioneer work in this field by HOUK and HORNER. This Committee has followed the development and use of this apparatus from its inception.

Many lines of research, both of practical importance and of scientific interest are still available through the use of the sprinkled-plat infiltrometer. It appears, however, that the apparatus is capable of giving results comparable with those occurring under natural runoff-conditions but requires material improvement in order to (a) eliminate marginal effects, (b) permit the use of drop-sizes and rain-intensities more nearly comparable with those occurring in nature.

The Committee takes occasion to urge: (1) The Research Division of the Soil Conservation Service to stress researches on these problems; (2) because of their fundamental importance to

scientific hydrology, that the fullest cooperation be given on the part of other hydrologists in promoting and carrying out such researches.

It should be noted, however, that these problems are not merely problems of soil-technology, climatology, or even hydrology. Fundamentally they are problems in physics. Considering hydraulics as a branch of physics, these problems, and others like them which the Committee has encountered, are fundamentally physical problems; but they also involve various other sciences, including hydrology, hydraulics, meteorology, soil-technology, and a modicum of biology--the latter because the phenomena involved are in general related not only to the soil but also to the soil-cover or vegetation and the biologic life in the surface layer of the soil.

In view of this situation, it is obviously difficult to find research-workers possessing all the knowledge and training requisite to obtain the best results. The most common shortcoming among research-workers in hydrology seems to be lack of adequate knowledge of the fundamentals of physics and hydraulics. This applies not only to the men of the Soil Conservation Service but to research-workers of other Government bureaus and to practicing engineers.

The Committee urges, and has urged, not only in relation to the research-work of the Soil Conservation Service but elsewhere, that hydrologic data should be analyzed along complete lines, having full regard to the physical and hydraulic processes involved. Unless this is done, erroneous, incomplete, or purely empirical results may be obtained; and, in particular, it has been found that the use of averages of quantities which are not homogeneous may produce results which are misleading.

In relation to the matter of publication of research-data the Committee from the start has urged early publication of hydrologic data from field-stations, in a form sufficiently complete that they may be used for any desired purposes. The Committee is pleased to report substantial progress in this respect, particularly in relation to the publication of data from small drainage-basins collected under the direction of Mr. C. E. RAMSER. Attention is called to the series of bulletins entitled "Hydrologic studies," containing extensive files of such data from various field-experiment stations of the Soil Conservation Service.

In addition the Committee is greatly gratified to call attention to the publication of "Hydrologic Bulletin No. 1 - Hydrologic data, North Appalachian Experiment Station, Coshocton, Ohio, 1939". This is the first of a series of bulletins, the establishment of which was urged by the Advisory Committee. This Bulletin presents in full detail the results of a large number of storm-studies on small drainage-basins in such complete form that the results may be analyzed and used in almost any way that may be desired. Thus it forms the basis for an important contribution to scientific hydrology along various lines.

Another line of publication urged by the Committee, which has come to fruition, is the publication of hourly rainfall-data, not only for recording raingage-stations maintained by the Soil Conservation Service, but also through the able direction of Mr. MERRILL BERNARD, for the extensive network of recording raingages recently established throughout the United States. The Committee understands that this publication of hourly rainfall-data is being extended so as to include past records at regular Weather Bureau stations.

Much remains to be done, however, in the way of publication of original data in order to prevent their being stored away in vaults "for the spiders to read," as aptly expressed by L. K. SHERMAN. In particular, extensive series of valuable data have been collected from permanent runoff-plats at various experiment-stations and research-stations of the United States Department of Agriculture and very few of these data as yet have been either published or analyzed. These experiments give runoff-data from natural rainfall under fully controlled conditions as to soil, vegetal cover, slope, and cultivation. Unfortunately, in connection with many of these strip or permanent plats, only the total runoff is measured. The Committee has urged the installation of recording runoff-gages on all or most of these plats, and much has been accomplished in this respect. However, many plats still remain without recording gages and under present war-conditions further installation of recording-runoff-gages is unlikely. In this case some delay in publication of analyses of the results may not have been detrimental because these plats present somewhat special and unusual problems in analysis, partly because of the lack of recording gages and partly for other reasons. For example, the results are undoubtedly affected materially by rain-shading in some cases where, for example, corn is grown on one plat alongside another plat with low-growing crops, such as grass or potatoes. If the rain falls at an angle, the plat containing the low-growing crop may receive materially less rain than the corn. Again, on plats with steep

slopes, if the rain falls at an angle, the amount of rain actually falling on the plat may be materially greater than that falling on an equal horizontal projected area or as measured by a raingage. Experiments are now being carried out by the Soil Conservation Service at Pullman, Washington, in this connection, and it is understood that these experiments have shown in some cases a difference of as much as 20 or 30 per cent in case of plats on a 30° slope.

In view of the present war-situation it seems inevitable that the research-work of the Soil Conservation Service should be somewhat curtailed. It is to be hoped, however, that the series of observations at field-research stations may be continued and that publication and analysis of the results may continue, at least along lines where the data are most urgently needed, either for practical application to flood-control and land-use problems or because of the contribution they will afford to the advancement of scientific hydrology.

Acknowledgment is made to Dr. M. L. NICHOLS, Chief of the Division of Research, Soil Conservation Service, and to those of his staff with whom the Committee has come most in contact, for their liberal cooperation.

Voorheesville, New York

DISCUSSION

M. L. NICHOLS (Soil Conservation Service, Washington, D.C.)--I feel that this is a very good report and that it contains some important and valuable suggestions. I think we will be able to follow out these suggestions in a general way, but not as fully as we would like, as we have just received notice of a rather critical cut in our appropriations.

We probably will be slowed up on our publications and have agreed to a cheaper form of publishing, in order to put them out at all. We will, of course, keep up the project on hydrology of winter runoff and sheet-flows and channel- and valley-storage that you mention specifically. However, we probably will fall down on the complete analyzing of the hydrographs. We will try, however, to do enough of this to avoid, as far as possible, any erroneous and empirical results, which you point out as a possible danger.

REPORT OF COMMITTEE ON GLACIERS, 1941-42

François E. Matthes, Chairman

(Published with the approval of the Director of the Geological Survey)

The membership of the Committee continues unchanged. It is as follows: HARRY FIELDING REID, Professor Emeritus of Geology, Johns Hopkins University, 608 Cathedral Street, Baltimore, Maryland; WILLIAM H. HOBBS, Professor Emeritus of Geology, University of Michigan, Ann Arbor, Michigan; LAWRENCE MARTIN, Chief, Division of Maps, Library of Congress, Washington, D.C.; J. E. CHURCH, Professor of Meteorology, Agricultural Experiment Station, University of Nevada, Reno, Nevada; WILLIAM O. FIELD, Jr., Explorer, 18 West Twelfth Street, New York City; OLIVER KEHRLEIN, Chairman, Committee on Glacier Studies, Sierra Club, 1050 Mills Tower, 220 Bush Street, San Francisco, California; KENNETH N. PHILLIPS, Associate Hydraulic Engineer, Water Resources Branch, Geological Survey, Chairman, Research Committee of the Mazamas, 606 Post-Office Building, Portland, Oregon; WILLIAM S. COOPER, Professor of Botany, University of Minnesota, Minneapolis, Minnesota; GERALD FITZGERALD, Senior Topographic Engineer, Alaska Branch, Geological Survey, Washington, D.C.; LAURENCE M. GOULD, Professor of Geology, Carleton College, Northfield, Minnesota; Dr. MAX H. DEMOREST, Department of Geology, Wesleyan University, Middletown, Connecticut; FRANÇOIS E. MATTHES (Chairman), Senior Geologist, Section of Glacial Geology, Geological Survey, Washington, D.C.

Recent research and publications by Committee members

WILLIAM O. FIELD, Jr., in company with Dr. DONALD B. LAWRENCE, of the University of Minnesota, visited Glacier Bay and several of the fiords southeast of Juneau, Alaska, on an expedition sponsored by the American Geographical Society. This was Mr. FIELD'S fourth visit to the coast of Alaska for the purpose of making observations on the changes that are taking place in the extent and volume of the glaciers. Favored by unusually good weather, he was able to occupy no

less than 49 triangulation-stations for the charting of the ice-fronts and determining their recession or advance since his last visit in 1935.

A preliminary report on the results of this work has been published by Mr. FIELD under the title, "Glacier studies in Alaska, 1941" [Geog. Rev., v. 32, No. 1, pp. 154-155 (1942)]. A somewhat fuller statement of the changes that were observed in the 28 glaciers visited is given in this report.

Dr. LAWRENCE studied the distribution and character of the vegetation, thereby continuing the type of ecological research which Professor WILLIAM S. COOPER, his senior associate in the Department of Botany at the University of Minnesota, has carried on along various parts of the Alaskan Coast in 1916, 1921, 1929, and 1935, and which has enabled him, notably, to shed valuable light on the large-scale oscillations which the glaciers in the Glacier Bay Region have made during Post-Pleistocene time.

Professor COOPER himself has recently produced three papers that should be of interest to hydrologists as well as to glaciologists, climatologists, and ecologists. The first of these papers to be published is entitled "Vegetation of the Prince William Sound Region, Alaska; with a brief excursion into Post-Pleistocene climatic history" [Ecologic Mono., v. 12, No. 1, pp. 1-22 (1942)]. Professor COOPER significantly concludes that the long period of ice-contraction that preceded the last great ice-advance in coastal Alaska "was of a magnitude so great as to be a major, or perhaps the major event of middle Post-Pleistocene time; that it corresponds with the warm, or warm-dry (xerothermic) period first suggested by European students, accepted by a majority of American specialists in pollen analysis, and supported by other evidence derived from varied fields of research."

In his paper on "An isolated colony of plants on a glacier-clad mountain" [Bull. Torrey Bot. Club, v. 69, pp. 429-433 (1942)], he describes 15 species of small plants that had been collected by Mr. and Mrs. BRADFORD WASHBURN when they made the ascent of snow-capped Mount Bertha, on the east flank of the Fairweather Range, Alaska, in 1940. Although growing at altitudes of 4,100 to 6,000 feet, far above the vast ice-field known as the Brady Glacier, these plants include eight lowland species that normally do not occur in the Alpine Zone. Professor COOPER dismisses the possibility that under present conditions the seeds could have been wafted up by the wind from the coastal lowlands over long stretches of ice-covered mountain country. Still less would such a migration have been possible a few centuries ago, when this part of Alaska, including the Glacier Bay Region, was far more extensively buried under glacier-ice than it is today. He therefore prefers the hypothesis that the colony of plants is a remnant of a once continuous vegetal cover that reached high up on the mountain flanks during the relatively warm period which preceded the recent glacier-expansion, and during which the Glacier Bay Region was broadly mantled with forests.

In the third paper, "Contributions of botanical science to the knowledge of postglacial climates," which he presented at the joint meeting of the Geological Society of America and the American Association for the Advancement of Science, in celebration of the 50th anniversary of the University of Chicago, in September, 1941 [to be published in J. Geol.], Professor COOPER has reviewed the different types of botanical evidence--paleobotanical and ecological--that are indicative of climatic changes during Post-Pleistocene time. The statistical studies that have been made of different types of tree-pollen entombed at successive levels in Post-Pleistocene peat-bogs, in particular, have proved helpful in establishing with reasonable certainty a climatic sequence from arctic through cool-moist to warm-dry conditions culminating about the middle of the Post-Pleistocene interval, and a return to somewhat cooler and moister conditions during the last few thousand years. These changes are reflected also in the present distribution of plant-communities, more especially of isolated colonies of trees and other plants that are clearly relics of vegetation that was dominant during the "climatic optimum" of Post-Pleistocene time. He further shows how these botanical evidences harmonize with Post-Pleistocene glacier history in Alaska, with the drying up and subsequent reappearance of saline lakes in the Great Basin, with the parallel extinction and subsequent rebirth of small glaciers on the mountains of the western United States, with the history of the formation of continental sand-dunes, and with the trend of the geothermal gradient in deep mines [abstract in Bull. Geol. Soc. Amer., v. 52, No. 12, Part 2, p. 2023 (1941)].

Dr. DEMOREST continued his research on the recrystallization of glacier-ice under deformational stresses such as occur in moving glaciers. This research was carried on with the aid of a grant from the Geological Society of America. Additional aid in the past two years was given by Yale University and the National Research Council. During the coming year a Guggenheim Fellowship granted to Dr. DEMOREST will enable him to carry this difficult work forward.

Ice for the experiments, which are conducted in a sub-freezing laboratory at Yale University, consists of selected pieces cut from the glaciers of Mount Rainier and of pond-ice. This research, the first of its kind to be conducted in this country, was begun in 1939 and has involved, in addition to the work in the laboratory, six months of field-studies on Mount Rainier.

Preliminary accounts of the methods used and the results obtained have been published in:

(1) Ice-deformation in the flow of glaciers (abstract), Trans. Amer. Geophys. Union, p. 525, 1941.

(2) Processes of ice-deformation within glaciers (abstract), Bull. Geol. Soc. Amer., v. 52, p. 1897, 1941.

(3) Techniques for making thin-section studies of glacier-ice (abstract), Bull. Geol. Soc. Amer., v. 52, p. 2013, 1941.

(4) Glacier regimens and ice-movements within glaciers, being Part I of a joint paper with Professor RICHARD FOSTER FLINT, entitled "Glacier thinning during deglaciation," Amer. J. Sci., v. 240, pp. 29-66, 1942. In this paper Dr. DEMOREST has presented a mechanical analysis of the stresses that induce motion in glaciers of different types and under different conditions. It should help in clarifying a number of points relating to the mechanism of glacier-motion that have long been subjects of controversy.

(5) Greenland's glacial anticyclone, A review, Amer. J. Sci., v. 239, pp. 771-778, 1941. In this critical review of the glaciologic and meteorologic studies that were made by the successive University of Michigan Greenland Expeditions, Dr. DEMOREST shows that the concept of anticyclonic nourishment of ice-sheets has not yet been demonstrated, and he points out the need for further factual information on the relative roles played by cyclonic and anticyclonic precipitation over ice-sheets.

The Chairman of this Committee devoted a large part of the year 1941 to the preparation of a chapter on "Glaciers" for the volume on "Hydrology" [No. 9 of the "Physics of the Earth" Series, edited by Dr. O. E. MEINZER, McGraw-Hill Book Co., Inc., New York and London (1942)]. The chapter consists of two parts, the first dealing with various aspects of the alimentation, regimen, crystalline texture, and motion of glaciers; the second comprising a synopsis of the data that are now at hand concerning the secular variations of glaciers during historic times and, more generally, during the Post-Pleistocene interval. Prominence is given, in the first part, to the notable advances that have been made recently toward a clearer understanding of the mechanics of glacier-motion. Those advances have been achieved both through carefully planned measurements on glaciers and through crystallographic studies of firn and ice selected from different parts of glaciers with reference to the distribution of the deforming stresses. As a result it is now reasonably certain that glacier-motion is primarily of the nature of plastic deformation, or "solid flow," and that the transformation of porous firn into compact, glassy glacier-ice is effected by recrystallization induced by the deforming stresses. On the other hand, it is equally certain that shearing and overthrusting occur in association with plastic deformation, being called forth wherever the differential flow-movement is obstructed, either by slower-moving masses or by wholly stationary ones. The two schools of thought that have so long opposed each other, the one stressing flowage, the other shearing, thus are seen to be both right to some extent, and, through DEMOREST'S deductive analysis, the manner in which the two types of motion are related to each other at last stands explained on mechanical grounds.

The fundamental soundness of DEMOREST'S distinction between "gravity-flow" and "extrusion-flow" also is recognized. The former occurs typically in mountain-glaciers moving down fairly steep beds under the direct pull of gravity. The latter is dominant in ice-caps and ice-sheets spread out over terrain that precludes gravity-flow; it is induced by differential pressures within the ice-masses themselves. Apperception of the mechanical principles involved in those two contrasting modes of flow doubtless will go far to dispel many of the misconceptions regarding the motion of glaciers of different types that have long been current.

In the second part of the chapter the aim has been to develop the fact that the world-wide shrinkage of glaciers which is now in progress is not part of a continuous process of deglaciation that supposedly began toward the end of the Pleistocene epoch, but only a brief episode in modern--that is, late Post-Pleistocene glacier-history. It set in no farther back than the 1850's, after one of the greatest glacier-advances that has occurred since the end of the Pleistocene ice-age. That glacier-advance was the latest of a series of such advances that have followed one another during

the past three centuries and that together comprised the climactic phases of a mild recrudescence of glacial conditions--a separate "little ice-age," that began about 4,000 years ago, after the prolonged warm period, or "climatic optimum," of mid-Post-Pleistocene time.

Existing glaciers fall into two categories differing widely in age

In the reports of this Committee for 1939 and 1940 it was shown that there is good reason to believe that the present cirque-glaciers on the Sierra Nevada of California are not relics of the Pleistocene ice-age, as commonly supposed, but representatives of a new generation of ice-bodies that originated only about 4,000 years ago, with the return of cooler and moister conditions after the warm and dry period--the "climatic optimum"--of mid-Post-Pleistocene time. A clue to the approximate date of their origin was found in the age of Owens Lake, which lies at the eastern base of the Sierra Nevada and is fed very largely by the melt-water that comes from the heavy winter snows on that range. From the salt-content of that lake and the rate of inflow of dissolved salines GALE [see 1 of "References" at end of report] had calculated that the present concentration had required, in round numbers, 4,000 years. As ANTEVS [2] has pointed out, however, the lake cannot, in view of its low salinity, be a remnant of the much larger and deeper lake that occupied Owens Valley in Pleistocene times, but must be a new pool formed in a freshened, saltless basin. In that respect it is analogous to Abert Lake and Summer Lake, in southern Oregon, and other enclosed pools of moderate salinity in the Great Basin that have been formed within the last few thousand years in depressions formerly occupied by large Pleistocene lakes.

It occurred to the present writer that, inasmuch as Owens Lake and the glaciers of the Sierra Nevada are both dependent for their maintenance upon sufficient snowfall and sufficiently low summer temperatures, the same climatic change which resulted in the rebirth of the lake very probably also brought back the glaciers. Those ice-bodies, therefore, would be of about the same age as the lake--that is, roughly 4,000 years old. They may be younger but they can hardly be older, for it does not seem possible, to judge from the rapid rate at which they have been wasting away during the past decade, that they could have survived the 3,000 years of excessive warmth of the "climatic optimum." Their youth is further attested by the extremely fresh, raw appearance of their moraines and by the fact that these in some instances still contain large cores of glacier-ice.

HANSON [3], as far back as 1934, had concluded from his calculation of the age of the Bear River Delta, at the head of Portland Canal, in British Columbia, that the cirque-glaciers now existing at the head of the Bear River cannot be more than 3,600 years old and are not to be regarded as shrunken remnants of the large glaciers of the Pleistocene epoch. There appears to be, then, a remarkably close parallel between the history of the rebirth of the Sierra Glaciers and that of the rebirth of the cirque-glaciers in British Columbia, and this parallelism justifies the broad generalization that probably the majority of the present cirque-glaciers on the Cordilleran ranges of North America, from California northward to Alaska, belong to this new generation of ice-bodies that came into being during the "little ice-age" of the last 4,000 years.

However, it was pointed out also in the report for 1939 that the main ice-streams on such peaks as Mount Baker, Mount Rainier, and Mount Olympus probably do not belong to this class of reborn glaciers but, like the still larger glaciers of British Columbia and Alaska and the vast ice-sheets of Greenland and Antarctica, have persisted continuously since the last glacial maximum of the Pleistocene epoch. They doubtless contracted considerably during the "climatic optimum" of mid-Post-Pleistocene time but reexpanded during the "little ice-age." On our western mountains--and, indeed, elsewhere in the world--there are, then, glaciers of two entirely different categories, namely, (1) glaciers that have been in existence uninterruptedly for 50,000 years or more and (2) glaciers that originated during the "little ice-age," less than 4,000 years ago.

It was not explained in the afore-mentioned reports of this Committee, how the glaciers of these two categories might be differentiated from one another, and the reader may have remained under the impression that magnitude is the main criterion. It is now proposed to show that the fundamental criterion is to be found in the contrasting relations which the sources of the glaciers of these two categories bear to the present regional snow-line. The glaciers that today have their sources at altitudes more than 1,000 feet above the regional snow-line with considerable certainty have persisted continuously ever since the Pleistocene ice-age, but those glaciers whose sources lie in cirques far below the regional snow-line--as much as 2,000 or 3,000 feet below it--can hardly have survived the prolonged warmth of the "climatic optimum" and doubtless are products of the "little ice-age."

The underlying reason is that during the "climatic optimum" the regional snow-line, to judge from many evidences of an upward shift of the timber-line on the mountains of central and northern

Europe, must have risen fully 1,000 feet above its present general level. Paleobotanical researches have demonstrated, for instance, that during mid-Post-Pleistocene time the fir forest in southwestern Norway reached altitudes about 1,000 feet higher than its present upper limit [4, p. 446]. Discoveries of plant-remains in peat-deposits at high altitudes in the Alps likewise have established the fact that the timber-line there then lay 1,000 to 1,300 feet above its present level [5, p. 359]. These determinations are now generally accepted by European scientists and are in harmony with the numerous proofs of the northward advance of warmth-loving species of deciduous trees during mid-Post-Pleistocene time and of their subsequent withdrawal to more southerly limits. It is, indeed, largely upon these mutually consistent paleobotanical evidences that the concept of the "climatic optimum" is founded [4, pp. 442-443].

In the continental United States entirely convincing evidence of a similar upward shift of the timber-line during mid-Post-Pleistocene time appears to be still lacking, but that is due probably to insufficient research, for, as is well known, there is plenty of evidence that in North America, as in Europe, the warmth-loving trees advanced considerably beyond their present northern limits, and it stands to reason that that horizontal advance was coupled with a rise of the timber-line to higher altitudes on the mountains.

It is quite possible that some of the "buried forests" on the flanks of Mount Hood, in Oregon, which were briefly alluded to in the reports of this Committee for 1932 and 1941, afford evidence of a former upward shift of the timber-line, though their status is not yet wholly clear. The mere fact, however, that the logs of the "Stadter Buried Forest," which lie in the present timber-line zone, have rings of growth as thick as those of the trees that now grow at the foot of the mountain--ten times as thick as those of typical timber-line trees--would seem to point rather definitely to a former rise of the timber-line of fully 1,000 feet.

Highly significant, further, is the testimony of the isolated colony of plants which the WASHBURNS discovered on a high shoulder of ice-clad Mount Bertha, on the Fairweather Range of Alaska. As pointed out above in the review of COOPER'S paper on this colony of plants, the facts in the case suggest strongly that it is a remnant of a once continuous vegetal cover which extended broadly over the country of moderate elevation around Glacier Bay and reached far up on the neighboring mountains at a time when the climate was considerably milder than it is today. That this was during the same prolonged warm period in which the fir and hemlock forest, whose stumps are now being brought to view as a result of the recession of the glaciers, flourished in the Glacier Bay Region, can hardly be doubted. That warm period COOPER holds to be probably identical with the "climatic optimum" of the European botanists.

The marked upward shift of the timber-line that was determined in central and northern Europe has been quite logically interpreted as implying a corresponding upward shift of the snow-line. For good climatologic reasons the two lines must remain about 2,500 to 3,000 feet apart in altitude. It follows that during the "climatic optimum" many of the lesser European glaciers went out of existence and the larger ones were much reduced in size. There is every reason to believe that the American glaciers were similarily affected. What really happened is, that these glaciers which now head, say, 3,000 feet above the regional snow-line, then headed only about 2,000 feet above it, but still had considerable gathering grounds left for their alimentation, while the lesser glaciers originating in cirques 2,000 to 3,000 feet below the regional snow-line then lay a full 1,000 feet lower still with respect to the zone of snow-accumulation and either vanished entirely or dwindled to insignificant ice-patches, owing to lessened snow-supply and greater atmospheric warmth.

Before proceeding, with these ideas in mind, to an examination of the more important glacier-districts in the western United States, it is necessary to digress in order to state what is meant by the regional snow-line and to explain how it comes that cirque-glaciers can exist as much as 2,000 to 3,000 feet below it.

The regional snow-line--There has been much confusion of thought as to what properly constitutes the snow-line, and several different definitions have been offered. To discuss them all would lead too far afield; nor would it serve the present purpose, as all of them, so far as the writer knows, were framed in disregard of the fact that some glaciers originate above the snow-line and others below it.

The prevailing concept--the one that is commonly expressed, or implied, in the text-books and dictionaries--is that the snow-line marks the lower limit of the region of "perpetual snow." As a matter of fact, however, there is no such thing as "perpetual snow," and for clear thinking it is desirable to avoid that expression. If any large part of a mountain range of polar land is perenni-

ally blanketed with snow, if its snow-cover never melts away, then snow is constantly accumulating there in excess of wastage and forming firn and, ultimately, glacier-ice. The snow-line, therefore, is really an ice-line, but it would not help matters to change its name to "ice-line," as all of the larger glaciers extend far below the zone of snow-accumulation and, as already indicated, many cirque-glaciers originate below it, paradoxical though that may sound.

The highest level to which the annual cover of fresh snow retreats up the mountain sides during the melting season is by some European glaciologists regarded as the true snow-line; but this, the autumnal snow-line, varies greatly in altitude, sometimes as much as 2,000 feet, from one year to the next, and is too unstable a feature to serve as a reference-line of climatologic significance. Nor is it, on boldly sculptured mountains, at all a sharply defined, continuous line. It is a patchy zone having an altitude range of 1,000 to 3,000 feet. Within it temporary snow-drifts linger here and there, on the shady and/or leeward sides of crests, spurs, cliffs, and benches; within it residues of avalanched snow also remain lying for weeks and months at the base of avalanche-chutes, or in the chutes themselves.

At the upper margin of this unstable, patchy zone lie the more permanent firn-fields that vary appreciably only as the result of climatic changes of a secular order. These firn-fields form the ragged lower fringe of the zone of snow-accumulation and glacier-generation--the zone in which the land is largely or wholly covered with firn and glacier-ice. Only two classes of surfaces in that zone ordinarily remain bare--mountain-sides so steep that the snow is shed from them in avalanches, and slopes or summits from which the snow is periodically swept by violent winds. The lower limits of that zone, though varying locally in altitude, and irregular in detail, constitute, in the writer's opinion, the only stable snow-line that can be consistently traced over any large extent of territory. For it the term regional snow-line is proposed, to contrast with the purely local snow-lines, or firn-lines, on individual cirque-glaciers, which are largely independent of it, as will be shown presently.

The regional snow-line, accordingly, may be defined as the lower margin of the zone in which under a given set of climatic conditions snow accumulates in excess of wastage and forms glacier-ice on all parts of the land save those from which the snow is removed periodically either by avalanches or by wind-action.

The firn-line on glaciers--That cirque-glaciers can and do originate at altitudes far below the regional snow-line has been recognized by a number of observers, but the climatologic significance of the fact apparently has not been fully appreciated. T. C. CHAMBERLIN [6] and R. D. SALISBURY [7] were among the first to note the phenomenon while on their explorations along the west coast of Greenland, in 1894. In cirques indenting the coastal cliffs of certain islands they observed small independent glaciers situated far below the margins of the ice-caps that covered the uplands. Such independent cirque-glaciers occurred even on islands too low to bear ice-caps. The explanation suggested itself that these small glaciers are nourished largely by windblown snow entrapped in the hollows, and only secondarily by direct precipitation.

In Norway, RICHTER [8] similarly noted the existence of small glaciers in cirques situated far below the margins of the ice-caps that lie on the plateau-like uplands, and he rightly attributed the maintenance of those independent glaciers to the concentration and conservation of large quantities of windblown snow in the shady, mostly northward opening cirques. KALESNIK [9] has reported the occurrence of cirque-glaciers of this type in parts of the Ural Mountains that are not high enough to have a regional snow-line.

Other examples might be cited, but the foregoing will suffice to establish the fact that because the wind is a powerful conveyor of snow--both of snow in course of precipitation and snow that has fallen--deeply inset cirques favorably oriented with respect to wind-direction, become effective traps for large quantities of drifting snow derived from adjoining areas of mountain land--quantities that, together with those contributed by direct precipitation, suffice to generate glaciers. If, moreover, such cirques are so oriented as to afford the snow accumulated in them considerable protection from insolation, they become conservatories as well as places of concentration, and as a result glaciers are generated in them at altitudes far below the regional snow-line. Cirque-glaciers of this type may be formed, even, on mountains that have no snow-line at all. They have been referred to as "drift-glaciers" and "snowdrift-glaciers," but those terms have connotations so misleading that it seems best to avoid using them. Cirque-glaciers that are alimentated primarily by the wind, indeed, do not differ in physical characteristics from glaciers that are alimentated primarily by direct precipitation, and, besides, in boldly sculptured alpine regions all glaciers are wind-fed in greater or less degree, and no distinction can be made on the basis of mode of alimentation.

From all this it follows that every glacier that lies recessed between bold peaks and spurs has a snow-line of its own situated more or less below the regional snow-line. For that reason it is desirable that their individual snow-lines be designated by a separate term. As the term firn-line is already much used by European glaciologists, it is urged that it be generally adopted also by American students of glaciers. Only on ice-caps and ice-sheets having simple and fairly smooth surface-configurations, the firn-line and the regional snow-line are practically one. On an ice-mantled dome on which topographically controlled wind-shadows and sun-shadows have only subordinate influence on the distribution of the snow, the two lines are, in general, only locally apart; but on boldly sculptured mountains they may differ as much as 2,000 feet to 3,000 feet in altitude.

Application to the glaciers of the western United States

A survey of the glaciers now existing on the western mountains of the continental United States, with the concepts just outlined in mind, readily enables one to distinguish those heading so high above the regional snow-line that unquestionably they have persisted since the Pleistocene ice-age, from those heading so far below the regional snow-line that they can hardly have survived the warmth of the "climatic optimum," but must have been formed during the "little ice-age." There are also, of course, intermediate cases that cannot with certainty be classified with either group, for glaciers do originate at many different levels above and below the regional snow-line.

A detailed analysis such as is really required, of the lay of each individual glacier with respect to the surrounding topography and the wind- and insolation-factors that affect its regimen, cannot be made here; hence only a preliminary sketch is offered, designed to indicate the general distribution of what for convenience may be called the "ancient" and the "modern" glaciers.

Mount Rainier is a good locality in which to begin, as glaciers originating at many different altitudes there lie in close proximity to one another and are readily compared; also, because there is available a topographic map of the Park, on the scale of 1:62,500, on which the glaciers are delineated and contoured with the same accuracy as the land-forms. In fact, the study can be based in large part on the topographic map itself.

The great cone of Mount Rainier, which reaches an altitude of 14,408 feet, and is fairly draped with long glaciers that descend from its summit platform, obviously rises high above the regional snow-line, whereas the surrounding mountain crests of the Cascade Range, which vary in altitude from 5,500 to somewhat over 7,000 feet, and bear only scattered cirque-glaciers, lie definitely below it. To determine the altitude of the regional snow-line on the flanks of Mount Rainier one must look for slopes of moderate inclination that are not covered with glacier-ice derived from higher altitudes, but bear glacier-ice formed in situ. Allowance must be made, on the one hand, for excessive accumulations of windblown snow on the leeward sides of crests and spurs, and on the other hand, for the effects of strong deflation on the windward sides. The winds that most potently affect the distribution of snow on Mount Rainier come from the west and southwest. Without going into the details of such an analysis it may be said that it shows the regional snow-line to have a mean altitude of somewhat over 9,000 feet.

Taking 9,000 feet as a working figure, it is clear at once that the great ice-streams that originate on the summit platform, at altitudes of 13,500 to 14,400 feet, head 4,500 to 5,400 feet above the regional snow-line. Those ice-streams--the Winthrop, Emmons, Ingraham-Cowlitz, Nisqually, Kautz, and Tahoma--therefore quite surely have persisted uninterruptedly throughout Post-Pleistocene time, for, with a maximum rise of the regional snow-line during the "climatic optimum," of, say, 1,500 feet, they still would have headed 3,000 to 4,000 feet above that line and would have had fairly large gathering grounds. It is possible, even, that during part of the time the summit platform then was more heavily loaded with ice than it now is, for the rise of the regional snow-line probably was accompanied by a corresponding rise of the zone of maximum snow-precipitation, which at present lies below the summit platform. At the same time, the greater warmth at the lower levels very probably more than offset any increase of alimentation on the summit platform and caused the lower portions of the glaciers to melt away.

Four other large ice-streams on Mount Rainier--the Carbon, North Mowich, South Mowich, and Puyallup--head in cirques inset in the flanks of the peak at levels ranging from 9,700 to 12,000 feet, but they, too, are in large measure dependent for sustenance upon the ice-accumulations on the summit platform, for they receive large and frequent accessions in the form of avalanches. They, too, therefore, doubtless survived the warmth of the "climatic optimum."

One other great ice-stream, the South Tahoma Glacier, heads in a cirque but, unlike the preceding, receives no contributions from the summit platform. Nevertheless, it probably also persisted throughout Post-Pleistocene time, for it heads at an altitude of about 10,500 feet, receives large quantities of windblown snow from the cliffs above it and still larger quantities from the broad surface of its western neighbor, the Tahoma Glacier. Thus, it will be seen, all of the eleven main ice-streams of Mount Rainier belong, with little doubt, to the category of "ancient" glaciers.

Attention is next invited to those lesser glaciers in the vicinity of Mount Rainier that clearly lie far below the regional snow-line. Typical examples are the Sarvent Glaciers, which occupy small cirques carved in the north flank of the ridge that extends from the Panhandle Gap eastward to the Cowlitz Chimneys. The highest knobs on that ridge attain altitudes of only 7,300 to 7,400 feet, and westward the ridge declines gradually to 6,700 feet at the Panhandle Gap. It therefore lies entirely below the regional snow-line, in part more than 2,000 feet below it. Nor does it bear any permanent ice on its south side, which is both wind-swept and strongly insolated. The Sarvent Glaciers, on the other hand, obviously are of the largely wind-fed type and, in addition, are so situated as to receive but little solar heat. Much of the time they lie in the shadows cast by the cliffs and pinnacles at their heads, and even at high noon in summer the Sun's rays strike their steeply northward sloping surfaces at a large angle of incidence, so that much of the heat is reflected. The largest glacier of the group heads at an altitude of less than 7,000 feet, and the westernmost heads north of the Panhandle Gap, at an altitude of only 6,600 feet--that is, fully 2,400 feet below the regional snow-line.

It can hardly be supposed that these small glaciers, which are rather delicately adjusted to recent climatic conditions, could have survived a prolonged warm period during which the regional snow-line rose 1,000 to 1,500 feet above its present general level; there is therefore good reason to believe that they came into existence during the "little ice-age" of the last 4,000 years.

Intermediate in position between the great ice-streams of Mount Rainier, which have their sources 4,500 to 5,400 feet above the regional snow-line, and the little Sarvent Glaciers, which originate at altitudes 2,000 to 2,400 feet below it, are such glaciers as the Fryingpan, Whitman, and Russell. The Fryingpan and Whitman head on the northeast and southeast flanks, respectively, of Little Tahoma, at altitudes of somewhat over 10,500 feet. The former is three miles long and covers a triangular area of about two square miles; the latter is 1.6 miles long and has an area of 0.81 square mile. The upward shift of the regional snow-line of 1,000 to 1,500 feet during the "climatic optimum" probably did not destroy them entirely, for both of them lie on the leeward side of Little Tahoma and are abundantly supplied with windblown snow derived from the large expanses of glacier-surface on the east flank of Mount Rainier. During the "climatic optimum," however, they doubtless received less snow from that source and also less snow by direct precipitation; in addition, they were exposed to higher air-temperatures, and so, very probably, they were greatly reduced in size and restricted to the uppermost portions of their present tracts.

The Russell Glacier, on the north-northwest side of Mount Rainier, is 2.6 miles long and has an area of nearly two square miles. Its highest tip reaches an altitude of about 9,500 feet, but only a small part of its sustenance comes from that quarter; the bulk undoubtedly consists of windblown snow that gathers on the leeward side of a low crest two miles long and declining gradually to an altitude of 7,200 feet. It may perhaps seem incredible that so extensive an ice-mass could be generated largely by windblown snow at altitudes well below the regional snow-line, but the fact that the windward side of the sheltering crest is for the most part bare of ice removes all possible doubt. The Russell Glacier probably did not exist as a connected ice-mass during the "climatic optimum" but was reduced to a few narrow strips of ice in the immediate wind-shadows of the more prominent parts of the sheltering ridge. It is undoubtedly a product of the "little ice-age," yet close to the border-line between the "ancient" and the "modern" glaciers.

A similar analysis can be made of the glacier-system of each of the great peaks of the Pacific Northwest and, more broadly, of the glacier-systems of the entire Cascade Range, the Sierra Nevada, and the numerous ranges of the Rocky Mountains within the continental United States, though not in every instance with the accuracy that is attainable in the case of Mount Rainier, for only a few of the mountain districts in question have been mapped in sufficient detail. Only a rapid survey of the field will here be made to show in a preliminary way which of our western mountains rise enough above the regional snow-line to bear glaciers that have persisted from the Pleistocene ice-age, and which bear only glaciers of the "little ice-age."

To begin at the north, Mount Baker, in latitude 48° 45′, has an elevation of 10,750 feet; but in that district, 30 miles from Puget Sound, the regional snow-line is at an altitude of only 6,000 to 6,500 feet, hence there can be no doubt that all of Mount Baker's major glaciers have persisted

since Pleistocene time. The same must be true of the glaciers on Mount Shuksan, near-by, which has an elevation of 9,038 feet. The surrounding mountain crests, which range in altitude from 5,000 to over 6,000 feet, bear no ice at all.

Eastward the regional snow-line rises by degrees towards the crest of the Cascade Range, which is 50 miles distant from Puget Sound. There peaks 8,000 to 8,500 feet high are free of ice, and the snow-line evidently is at an altitude of at least 9,000 feet. Only Glacier Peak, which has an elevation of 10,436 feet, bears glaciers that have persisted from the Pleistocene ice-age. The numerous cirque-glaciers that head at altitudes as low as 7,000 and even 6,500 feet are in all probability "modern."

Nearness to the Pacific Ocean and consequent abundance of precipitation and cloudy skies combine to bring the regional snow-line on Mount Olympus (latitude 47° 48′) down to an altitude of only 6,000 feet. As the peak has an elevation of 7,964 feet, it is reasonably certain that its five major glaciers, heading at altitudes of 6,500 to 7,500 feet, have persisted throughout the Post-Pleistocene interval. Inasmuch as the upward shift of the regional snow-line during the "climatic optimum" was probably less in this region of pronounced maritime climate than farther inland, it is possible, even, that many of the cirque-glaciers heading at altitudes of 5,500 to 6,000 feet, on Mount Olympus and on its satellite peaks, were able to survive the warmth of mid-Post-Pleistocene time.

That Mount Rainier, which stands only about one degree of latitude farther south than Mount Olympus, should have a snow-line 3,000 feet higher than that peak, is explained chiefly by its position farther inland. Whereas Mount Olympus is only 46 miles distant from the ocean, Mount Rainier is 112 miles from it.

Southward, naturally, the regional snow-line rises by degrees. On Mount Adams (12,397 feet), which stands 45 miles south of Mount Rainier and almost as far from the coast-line as that peak, the snow-line lies presumably between 9,000 and 9,500 feet. Its major glaciers therefore doubtless have persisted from the Pleistocene ice-age. On Mount Saint Helens (9,697 feet), which stands in the same latitude as Mount Adams but 27 miles nearer the coast-line, the snow-line is probably a little lower. It is just low enough to permit the existence of a small firn-cap on the top of the peak. The ice-tongues that lie at lower levels on the flanks of Mount Saint Helens, on the other hand, clearly were formed during the "little ice-age."

On Mount Hood, in latitude 45° 23′, the regional snow-line lies, by estimation, at an altitude of 9,500 feet or even somewhat higher. As the peak has an altitude of 11,245 feet, it doubtless rose high enough above the regional snow-line during the "climatic optimum" to retain small glaciers throughout that warm period. They lay probably for the most part on its cool northern and northeastern slopes.

Whether Mount Jefferson, in latitude 44° 41′, retained any part of its glacier-system during the "climatic optimum" is less certain, for that peak has an elevation of 10,495 feet, and the regional snow-line on it is probably close to 10,000 feet. Most of the small glaciers on its sides are likely to be of the "modern" kind.

More definite inferences can be made regarding the age of the glaciers on the group of volcanic peaks known as the Three Sisters (latitude 44° 06′ to 44° 09′). South Sister, the highest of the three, and 10,354 feet in altitude, bears only a small body of firn and ice in the shady half of its cup-shaped crater. It is therefore just too low to have a snow-line, and it follows that North Sister, with an altitude of 10,094, and Middle Sister with an altitude of 10,053 feet, are fully 300 feet too low. As the 15 small ice-bodies that cling to the sides of the three peaks all originate at relatively low levels, they presumably are all "modern."

Still farther south only one peak remains that is high enough to have a snow-line, and that is Mount Shasta, in latitude 41° 24′. It is, in fact, the southermost peak in the entire continental United States that rises above the regional snow-line. It is 14,161 feet high, and the snow-line on it is presumably at an altitude between 13,000 and 14,000 feet. The precise altitude of that line is difficult to determine, owing to the effects of strong insolation on the south side and vigorous deflation by westerly and southwesterly winds. Together those two agencies keep the south half of the peak largely bare of ice to within a few hundred feet of the summit. Even the summit bears no real ice-cap but only a thin layer of firn and snow. It is entirely probable that during the "climatic optimum" Mount Shasta had no snow-line properly speaking and bore only small wind-fed cirque-glaciers high up on its northwest, north, and northeast flanks.

The Sierra Nevada, it readily follows from the foregoing, lies wholly below the level of the regional snow-line. Not even its highest peak, Mount Whitney, 14,495 feet in altitude, bears any permanent ice-field on its broad summit. The range nevertheless possesses 60 small glaciers and glacierets, but these are all of the largely wind-fed type and lie either in deep, shady cirques or at the base of north and northeast facing cliffs. Those in the northernmost group, situated in the vicinity of Matterhorn Peak, in latitude 38° 06′, head at altitudes of 11,000 to 11,500 feet, but those in the southernmost, or Palisade Group, situated 80 miles farther south, head at altitudes of about 13,000 feet. Two small glaciers of the Palisade Group have the distinction of being the southernmost living glaciers in the continental United States (disregarding certain vestigial ice-patches near and to the south of Mount Whitney). They lie on the north side of the crest that connects Middle Palisade (14,408 feet) with the Thumb (13,885 feet), in latitude 37° 04′.

It is to be noted that it was these small cirque-glaciers on the crest-line of the Sierra Nevada that were first identified as being representatives of a "modern" generation at most 4,000 years old. They constitute the type of the "little ice-age" glaciers.

Turning now to the Rocky Mountains, many more glaciers of the same "modern" generation are scattered over their numerous ranges. The highest peaks of the Lewis and Livingston Ranges, in Glacier National Park, Montana--Mount Cleveland (10,438 feet), Mount Jackson (10,023 feet), and Kintla Peak (10,001 feet)--are too sharp and too steep-sided to bear any ice, but the fact that Mount Merritt (9,944 feet) bears a glacier on its southeastward sloping shelf at altitudes ranging from 8,000 feet up to 9,700 feet, and the fact that Mount Blackfoot (9,597 feet), though itself bare, is surrounded by ice-covered crests at altitudes of about 9,000 feet, warrant the inference that the regional snow-line there is probably not far above 10,000 feet. Accepting 10,000 feet as a working figure, a survey of the glaciers in the Park reveals that, with the exception of the Blackfoot, Pumpelly, Harrison, Rainbow, and Kintla, the great majority head at altitudes 2,000 to 2,500 feet below the regional snow-line and can hardly have persisted from the Pleistocene ice-age. A few, even, lie 3,000 feet below the regional snow-line. The little Iceberg Glacier, which now has practically disappeared, in 1900 headed at altitudes between 6,200 and 6,300 feet--that is, 3,700 to 3,800 feet below the snow-line. It thus is manifest that, with the few exceptions mentioned, all of the ice-bodies in Glacier National Park are wind-fed cirque-glaciers of the "modern" generation.

Since in Glacier National Park, just south of the Canadian boundary line, only five glaciers out of 60 are possibly survivors from the Pleistocene ice-age, one would hardly expect to find any other glaciers of that "ancient" category farther south in the Rocky Mountains, yet there is reason to believe that several such glaciers exist in the Wind River Range, in latitude 43° 10′. That range has no regional snow-line, but its highest peaks--Gannett Peak (13,785 feet) and Fremont Peak (13,730 feet)--fall but little short of reaching the zone of snow-accumulation. Were they 14,000 feet high, both probably would bear permanent ice-caps. Now the glaciers of the Wind River Range all lie in cirques, and, as the majority of them are situated on the east side of the divide, there is little doubt that they are all alimented in large measure by westerly winds. At least seven of them, among which are the three glaciers on Gannett Peak, head at altitudes between 12,500 feet and 13,000 feet. It may reasonably be presumed, therefore, that these persisted throughout the "climatic optimum," when the regional snow-line rose to about 15,000 feet.

Farther south in the Rocky Mountains there exist only a few glacierets ensconced in northeast or east-facing cirques. Such are the Sprague, Tyndall, Andrews, and Taylor glaciers on the Continental Divide in Rocky Mountain National Park, Colorado, and the St. Vrain Glaciers and the Arapahoe Glacier, a short distance to the south of it (latitudes 40° 20′ to 40° 00′). The two southernmost lie on Blanca Peak, in the Sangre de Cristo Range, in latitude 37° 35′. All of these glacierets occupy sites that, to judge from their relations to the surrounding topography, are exceptionally favorable for the concentration and conservation of wind-driven snow. The mountains themselves, including the 14,000-foot peaks, are far too low to have a regional snow-line, owing to the continental character of the climate. As the glacierets lie at altitudes of only 12,000 to 12,500 feet, it is reasonably certain that they, like those of the Sierra Nevada, are products of the "little ice-age."

To sum up: Within the continental United States a total of perhaps 60 glaciers, distributed chiefly among the great peaks of the Olympic Mountains and the northern Cascade Range, can with reasonable certainty be said to have persisted from the Pleistocene ice-age. In addition five cirque-glaciers in Glacier National Park and seven in the Wind River Range probably belong to this "ancient" category of ice-bodies, but all the other glaciers on our Cordilleran ranges--and that means the vast majority of them, several hundred in number--with little doubt are of the "modern" kind.

In conclusion, it may not be inappropriate to remark that this distinction between "ancient" and "modern" glaciers is likely to have more than academic interest, for from several "modern" glaciers on our western ranges the runoff is being utilized for purposes essential to our civilization. Should, therefore, the regional snow-line again rise to the high level which it attained during the "climatic optimum" and cause those "modern" glaciers to vanish, the communities and industries that are dependent upon them would be hard hit.

That the regional snow-line already has risen appreciably during the past 40 years is to be inferred from the graphs published by KINCER [10, 11], which show that mean annual temperatures in many parts of North America (and elsewhere in the world) have been rising more or less steadily ever since the beginning of this century. It is evident also from the increasingly rapid rate at which our glaciers are wasting away. How much the regional snow-line has actually risen in the four decades is not known, but this much is clear, that if the rate of wastage that has prevailed during the 1930's continues unabated, the majority of our "modern" glaciers will cease to exist in less than half a century, and long before that time they will have been reduced to such a small size that their runoff will no longer have much practical value. Only the relatively small number of "ancient" glaciers will then remain as dependable sources of glacial water, and of these many will be greatly reduced in volume.

Variations of American glaciers reported in 1941

Glaciers of Mount Baker

PAUL T. KENNEDY'S report on recession-measurements, published in "The Mountaineer" [v. 34, p. 39 (1941)] contains the following statements: "This year's figures are more astounding than any previously recorded and show a great increase in recession during the past year. From 1940 to 1941 the Easton Glacier, on the south side of Mount Baker, receded 220 feet. The average annual recession from 1934 to 1940 was 151 feet. The Coleman Glacier, on the northwest side of Mount Baker, receded 190 feet during the past year, while its average from 1936 to 1940 was 67-1/2 feet per year."

Following are the complete recession-records of the two glaciers, based on measurements made by the Mountaineers Club of Seattle:

Year	Easton Glacier (feet)	Coleman Glacier (feet)
1934 - 1935	190	.....
1935 - 1936	170	.....
1936 - 1937	116	52
1937 - 1940	429 (143 per year)	218 (72-2/3 per year)
1940 - 1941	220	190

Mr. KENNEDY attributes the rather sudden increase in recession from 1940 to 1941 chiefly to the relatively light snowfall during last winter, and he cites the following precipitation figures: At Glacier Ranger Station, which is situated ten miles north of the Coleman Glacier, the total precipitation from December, 1939, through September, 1940, amounted to 44.84 inches, but during the corresponding period last year it amounted to only 32.57 inches.

Since 1910, to judge from a photograph taken in that year, the Easton Glacier has been shortened 4,935 feet. The average for the 31-year period was 159.2 feet per year--that is, considerably more than twice the average (79 feet) of the Nisqually Glacier, on Mount Rainier, during the same years. The Easton Glacier therefore continues to hold the record among the glaciers of the continental United States for sustained rapidity of recession. The Coleman Glacier, with an average of 92 feet for the last six years, is second. As was pointed out in previous reports of this Committee, these facts are all the more significant as Mount Baker is situated 134 miles to the north of Mount Rainier and much nearer the Pacific Ocean than that mountain.

Lyman Glacier, northern Cascade Range, Washington

The Lyman Glacier is one of the larger cirque-glaciers in the Chelan District of the northern Cascade Range. It lies in a deep amphitheater north of Chiwawa Mountain (8,300 feet), at the head of Railroad Creek, which empties into Lake Chelan. The runoff from this glacier is being utilized by the Washington Water Power Company for the generation of hydroelectric power. In the 1939 report of this Committee the recession-record of the Lyman Glacier, as furnished by Mr. E. H. COLLINS, of the Washington Water Power Company, was given from 1929 to 1938. In an article

entitled "The recession of Lyman Glacier, Washington" [J. Geol., v. 49, No. 7, pp. 764-771 (1941)] Dr. OTIS W. FREEMAN, of the Eastern Washington College of Education, has brought the recession-record up to September, 1940. The entire record follows (the measurements were made in each case in the month of September): 1929-1930, 65 feet; 1930-1931, 79 feet; 1931-1936 (5 years), 289 feet; 1936-1937, 55 feet; 1937-1938, 45 feet; 1938-1939, 52 feet; 1939-1940, 58 feet; total recession, 643 feet. The average recession for the 11-year period is 58 feet.

Dr. FREEMAN'S measurements show, further, that the terminus of the glacier is now 1,748 feet from a small moraine that is said to mark the approximate position of the ice-front "some 40 or 50 years ago." Recession from that point therefore appears to have proceeded at a rate of approximately 40 feet per year. The topographic map of the Stehekin Quadrangle, which was made by the United States Geological Survey in 1901-1902--that is, about 40 years ago--shows the Lyman Glacier as an ice-body having a length of 1.3 miles. It may be presumed, therefore, that by 1940 the glacier's length had been reduced to one mile.

Glaciers of Mount Rainier

The following data are taken from a brief report on glacier-measurements transmitted by Superintendent JOHN C. PRESTON, of Mount Rainier National Park:

Emmons Glacier in the autumn of 1941 had receded 89 feet from its position in the autumn of the previous year. The average recession for the preceding ten years is 85.6 feet. As the Emmons Glacier ends in a huge mass of stagnant and partly stagnant ice covered by ablation-moraine, these recession-figures are necessarily approximate. The record for any single year is likely to have little value, but the average for several years at least indicates the general trend.

Carbon Glacier had receded 54 feet since the autumn of 1940. The average recession for the preceding eight years is 29.5 feet. The Carbon Glacier terminates in a narrow canyon and has a fairly clean-cut front. The recession-measurements consequently are fairly precise.

South Tahoma Glacier had receded no less than 224 feet, as compared with an average for the preceding seven years of 62 feet. The South Tahoma Glacier, like the Emmons, has a broad, debris-covered terminus to which it is impossible to make precise measurements, but there is little doubt that its recession was greatly accelerated during the past year.

Paradise Glacier has such a broad front that it is necessary to measure recession at more than one point. At point A the ice had receded 80 feet, as compared with an average for the past eight years of 32.1 feet. At point B, on the southwest side of the terminus, a recession of 202 feet was measured, comparing with an average for the preceding years of 31.5 feet.

Stevens Glacier, formerly the southeastern lobe of the Paradise Glacier, in 1939 became detached from the parent mass by excessive ablation and since then has not been measured. It is now reduced to a patch of stagnant ice.

Nisqually Glacier, on October 1, 1941, had receded 125 feet since the autumn of 1940. The average recession for the preceding ten years is 72 feet; the average for the last 57 years is 46 feet. By way of supplement to these data the present writer offers the following synopsis of the entire recession-record of the Glacier since 1857:

Period	Recession, feet	Accumulated recession, feet	Mean recession, feet
1857 - 1885	760	760	27.1
1885 - 1892	140	900	20.0
1892 - 1910	900	1,800	50.0
1910 - 1918	410	2,210	58.6
1918 - 1931	915	3,125	70.7
1931 - 1941	792	3,917	79.2

Since 1892, therefore, the mean annual recession has doubled, trebled, and almost quadrupled. It is quite probable, moreover, though no conclusive proof is at hand, that recession was interrupted by a brief halt, or even a small readvance, between 1885 and 1892.

The fourth repetitive plane-table survey of the lower portion of the Nisqually Glacier was made by the United States Geological Survey, under its cooperative agreement with the city of Tacoma,

in the summer of 1941. The original plan called for a resurvey every fifth year, beginning in 1931. The second survey, accordingly, was made in 1936; but so greatly increased were the losses of ice due to surface-ablation during the following years, that it was decided to make the third survey in 1940 instead of in 1941. The amazing losses of ice revealed by that survey have been set forth by the report of the Committee for 1941. To round out the normal five-year period, however, a fourth survey was made in 1941.

While the first and second surveys were made on a scale of 1:4,800, and with a contour-interval of 20 feet, the third and fourth surveys were made on one-half as large a scale--1:9,600--and with a contour-interval of 50 feet, it having been found that data sufficiently accurate for the computation of losses in volume can thus be obtained at considerable saving in cost.

In his report on the survey of 1941 ARTHUR JOHNSON, Hydraulic Engineer of the United States Geological Survey, states that that survey was carried half a mile farther up the glacier than the survey of 1940 and to an altitude 1,000 feet higher, in order to include a part of the glacier where the rate of ablation often differs appreciably from that prevailing on the lower ice-tongue. The fourth survey, accordingly, was extended over a total stretch of 2-1/4 miles up from the terminus and to an altitude of 7,500 feet. The total area mapped comprises 475 acres. Comparison with the map made in 1940 reveals a moderate lowering of the ice-surface up to the 5,300-foot contour-line, but only inappreciable changes above that line.

In some years, it has been found, the glacier increases somewhat in thickness in the region above the vicinity of the 5,500-foot line, while it suffers considerable reduction below that line. This difference in conditions has led to some speculation as to the probable cause. In a recent letter KENNETH N. PHILLIPS, Associate Hydraulic Engineer, of the United States Geological Survey, has offered the tentative suggestion that the cause may be found in an upward shift of the zone of maximum precipitation during recent years.

"If the average temperature is gradually rising, as records appear to indicate, the capacity of the air to retain moisture without condensation is increased, and it should follow that the level of maximum precipitation should be higher than before. Under such conditions there could be greater melting at low levels from the increase in temperature, while at higher levels, where the greater part of the ice presumably is disposed of by glacier-flow, the increased snowfall might result in a greater accumulation of ice than could be carried off even with the steeper surface gradient of the glacier."

Mr. PHILLIPS adds that similar conditions may possibly occur in the Alps and in Alaska, where some glaciers are receding but little, or are even advancing, while other glaciers near-by are steadily receding. "If the climate is becoming warmer in those places, and if the advancing glaciers generally have their gathering ground in a higher zone than the névé fields of the receding glaciers, the argument for an upward movement of the zone of greatest snowfall would have considerable support."

To the writer these suggestions seem entirely cogent, and they are borne out, he believes, by WILLIAM O. FIELD, JR.'S observations [12] on the coastal glaciers of Alaska.

To return to the investigations on the Nisqually Glacier in 1941, in addition to the mapping, two cross-profiles that had been laid out in 1930 were resurveyed. These cross-profiles are located about 3/4 mile and 1-1/4 mile, respectively, above the terminus. Comparison of the survey of 1941 of the lower profile with the original survey of 1930 shows that during the eleven years the ice-surface had been lowered by ablation a minimum of 20 feet near the western margin and a maximum of 100 feet at the middle of the glacier. The average reduction over the entire profile was 62 feet, representing a mean loss of 5-1/2 feet per year. In the central portion of the glacier the mean loss per year rose to a maximum of nine feet. Inasmuch as this part of the glacier is probably only 200 to 250 feet thick, it will readily be seen that at this rate of reduction it will be practically destroyed in a couple of decades.

On the upper profile the changes were more diverse. In 1941 the ice-surface east of the middle line had actually risen above its level of 1930. In some places it was as much as 30 feet higher. West of the middle line, on the other hand, the ice-surface had been lowered, the maximum reduction being 70 feet. The average change for the entire profile amounted to a loss of 16 feet, representing a mean loss of 1-1/2 feet per year; but in the west half of the glacier the mean loss per year reached a maximum of 6.4 feet. These marked local inequalities in the rate of reduction on this profile show how misleading the results of a few measurements at isolated points on a glacier may be.

Glaciers of Mount Hood

The Mazama Research Committee reports the following results of measurements made on two glaciers of Mount Hood in the autumn of 1941:

The Eliot Glacier on September 28, 1941, was found to be 19 feet shorter than on September 21, 1940. This shortening compares with 18 feet measured in 1940, and 64 feet measured in 1939. The two profile-lines that had been established across the glacier in 1940 were resurveyed in 1941, and the following vertical losses due to surface-ablation were determined: On the lower, or A-line, "in general less than five feet"; on the upper, or B-line, from 5 to 12 feet. These losses are of the same general order of magnitude as those measured on the Nisqually Glacier. It may be presumed, therefore, that the lower half of the Eliot Glacier faces the same fate as the terminal portion of the Nisqually Glacier and is likely to disappear in a couple of decades, if present climatic conditions persist unchanged.

Stones had been placed in 1940 on both profile-lines. The displacement of these stones by the forward movement of the ice was measured in 1941, and it was found that on the A-line, which is about 1,000 feet above the terminus, the maximum movement during the past year was only 4.5 feet, while on the B-line, located about half a mile farther up, the maximum movement was 10.5 feet. It is of interest to note that similar measurements made by the Mazamas in 1925-1928 on a line situated in about the same location as the present A-line revealed a maximum movement averaging 10.3 feet per year. The slowing down of the movement that has taken place since then is due doubtless to the considerable reduction in thickness which the glacier has suffered.

The Coe Glacier, whose recession had last been measured in 1939, was found to have been shortened 71 feet since then.

Glaciers of the Three Sisters, Oregon

To Miss RUTH E. HOPSON, of Eugene, Oregon, the Committee is indebted for the first information concerning the recession of the Collier Glacier, the largest of the 15 ice-bodies that adorn the group of volcanic peaks on the Cascade Range known as the Three Sisters. This glacier occupies a cirque that opens northward from Middle Sister and skirts the west base of North Sister. The topographic map of the Three Sisters Quadrangle, the surveys for which were made in 1928-1929, shows that in those years the Collier Glacier was 1.7 miles long and 3,800 feet broad in the middle of its course.

No actual measurement of recession or reduction in thickness have been made, but the three excellent photographs taken by Miss HOPSON, all from the same point, in 1934, 1936, and 1941, afford a good basis for eye-estimates of the losses in size and volume which the Collier Glacier has sustained during those years. From 1934 to 1936 only minor changes took place, but in the five years from 1936 to 1941 the ice-mass lost between 200 and 300 feet of its length and at least 50 feet of its thickness. Its lower portion, about one-quarter mile in length, is now so thin and so narrow that, with continuance of present climatic conditions, it probably will disappear altogether in another five years.

Glaciers of the Sierra Nevada, California

In his report on the glacier-measurements that were made in Yosemite National Park in 1941, M. E. BEATTY, Associate Park Naturalist, explains why it has been decided to discontinue recession-measurements to the fronts of the glaciers and hereafter to determine only the changes that are taking place in the thickness of the glaciers--that is, the amount by which their surface is being lowered by ablation or built up by excessive snowfalls. The fact--which at first was not suspected--is that most of the glaciers in the Park have no true ice-fronts, their terminal portions being thickly mantled with rock waste, and, further, that in many instances the ice beneath the rock waste, being effectively protected from ablation, has remained preserved in the form of a debris-covered ridge that simulates a moraine and now stands high above the cleaner ice of the glacier behind it. The "dead ice" in these false moraines is as a rule still connected with the main mass of the glacier, and measurements such as have been made to the frontal edge of the clean ice behind the false moraines therefore have no real significance.

That some of the false moraines are underlain by masses of "dead ice" was revealed some years ago by "cave-ins" that occurred at the fronts of several glaciers, due to the collapse of caverns melted in the ice beneath the rock waste by water percolating through from the glaciers. That some of the bolder false moraines even contain cores of "dead ice" 50 to 100 feet in height,

was suddenly disclosed in 1939, when the great embankment at the front of the Conness Glacier was neatly trenched by the water that had been temporarily impounded behind it [see report of this Committee for 1939-1940, Trans. Amer. Geophys. Union, 1940, pp. 399-400].

These revelations, it seems to the writer, fully justify the decision announced by Mr. BEATTY to discontinue further measurements of "recession" to the glaciers in and near Yosemite National Park, though an occasional check-up will be desirable on the conditions that exist at their lower ends. In the case of the Conness Glacier, indeed, the main ice-mass has become separated from the embankment and has a frontal edge resting on bedrock. The retreat of that frontal edge has been measured in past years. In seven years, from 1932 to 1939, it receded not less than 331 feet. If strong ablation continues it is to be expected that some of the other Sierra glaciers also will withdraw from their false moraines and, like the Conness Glacier, will be receding with fairly clean ice-fronts resting on bedrock and capable of being measured from year to year.

As might be expected, in view of the excessive snowfalls that took place during the winter of 1940-1941, the glaciers of Yosemite National Park suffered little or no reduction in thickness by ablation during the summer of 1941, but in some instances were built up by appreciable amounts. Resurvey of the profile-lines that had been established by Mr. BEATTY across the East Lyell and West Lyell glaciers shows that since the autumn of 1940 practically no change has occurred in the surface of the former, the gains being wiped out by the losses, while the surface of the latter was built up with new snow by amounts varying from 2.8 feet to 12.5 feet. Of course, these figures are not representative of the entire surfaces of these glaciers, and it may be presumed that both were built up by considerable amounts in their higher portions.

The statistics for the last eight years show that in spite of the increments received during the past year both glaciers are now thinner than they were in 1933. The West Lyell Glacier has lost 13.9 to 14.4 feet in thickness and the East Lyell Glacier 22.3 to 38.8 feet on the measured profiles.

The scientific value of the report for 1941 is greatly enhanced by the excellent photographs that accompany it. These photographs, taken by Park Naturalist C. FRANK BROCKMAN, portray the characteristics of the glaciers and the extent of the snow-cover at the end of the melting season in 1941 far more completely than any verbal descriptions could possibly do, and they constitute definite records for future comparison.

Glaciers of Glacier National Park, Montana

Park Naturalist M. V. WALKER reports unabated continuance of the rapid wasting of the glaciers in the Park during the summer of 1941. The snowfall during the preceding winter having been exceptionally light, most of the glaciers were practically stripped of new snow by the beginning of August. As a consequence their losses in length and in volume were very great.

The Sperry Glacier receded less than any of the three that were visited. The mean recession along its broad terminus was about 45 feet.

The main lobe of the Blackfoot Glacier, on the other hand, receded not less than 150 feet. The lobe is now very thin and therefore probably melts away more rapidly than the thicker ice mass above.

The Grinnell Glacier is reported to have receded 105 feet since last year, but owing to a change in the personnel of the Park Naturalist's staff and the fact that the new men were not familiar with the reference-points established by their predecessors, it is not entirely certain that the figure stated is correct.

Park Naturalist WALKER adds to his report complete tables of recession for all of the principal glaciers in the Park from the time that measurements were begun. Following totals are taken from these tables:

Glacier	Date when marker set	Last date measurement	Total recession, feet
Agassiz	1932	1938	654
Blackfoot	1932	1941	352
Sperry	1935	1941	485
Grinnell	1932	1941	451

It seems appropriate to supplement the foregoing data with certain estimates of long-time shrinkage by Dr. JAMES L. DYSON [13]. These estimates are based on comparisons of the detailed maps of the Grinnell, Sperry, and Jackson glaciers which he made for the National Park Service in 1937, 1938, and 1939, respectively, with the topographic maps of the Chief Mountain and Kintla quadrangles, which were made by the United States Geological Survey in 1900-1904, and with photographs taken in different years.

The Grinnell Glacier, when mapped in 1900, had a surface-area of about 0.93 square mile. In 1911, according to Dr. WILLIAM C. ALDEN'S estimate [14, p. 19], it still was about one square mile in extent. By 1937, however, its surface-area had shrunk to about 0.56 square mile--that is, about 40 per cent. The loss in volume was even greater. Dr. DYSON estimates it at about 50 per cent.

The Sperry Glacier in 1901 had a surface-area of about 1.31 square miles. By 1938 it had shrunk to an area of 0.61 square mile, or only 47 per cent of the area first mentioned.

The Jackson Glacier (formerly miscalled the west lobe of the Blackfoot Glacier) in 1901 covered an area of about 1.25 square miles and was 1.5 miles long. By 1939 it had shrunk to an area of 0.29 square mile and a length of one mile.

The Agassiz Glacier, when mapped in 1902, had an area of 1.40 square miles. By 1940 it had been resolved into two small and separate ice-bodies whose combined surface-areas amounted to 0.29 square mile, or 21 per cent of the glacier's original area.

For a full appreciation of the tremendous reduction in size which these glaciers have suffered, however, one must see Dr. DYSON'S outline maps showing the form and areal extent of each glacier at the beginning of the century and in the last few years [13, p. 816].

Dr. DYSON also describes the successive stages in the shrinkage of the small cirque-glacier that formerly produced the icebergs for which picturesque Iceberg Lake was famous. In 1920 that glacier still ended in an ice-cliff 90 to 100 feet high from which fragments fell into the water. By 1935 the glacier had been so greatly reduced in thickness that its surface sloped gently down to the lake, and by 1940 the glacier had shrunk so much that it no longer touched the water. No more icebergs float in the lake and its chalky tint, due to glacial rock flour, is gradually being replaced by a deeper blue.

The glacieret at the east foot of Clements Mountain (to the southeast of Logan Pass), which the present writer well remembers delineating on the topographic map in 1901, now has disappeared entirely.

The fact should be stressed, finally, that the conspicuous evidences of shrinkage and recession of glaciers cited above have been produced very largely since about 1920.

Glaciers of Rocky Mountain National Park, Colorado

Park Naturalist H. G. GREGG reports that only one ice-body in Rocky Mountain National Park--the Andrews Glacier-- was measured in 1941. A September snow-storm prevented approach to the Tyndall Glacier.

The Andrews Glacier is building a mud-delta in the lake that lies immediately in front of it, and as there is no solid rock in this delta that might serve as a permanent reference-point for recession-measurements, it is necessary to resort to measurements from stations on rocks to the northeast and southeast of the terminus. These measurements are, of course, not in line with the axis of the glacier; nevertheless, they afford a good index of the rate at which the ice-tongue is shrinking. Measurements from the northeast station in September, 1941, indicated a recession of 37-1/2 feet, as compared with nearly 40 feet in 1940.

Glaciers of Alaska

WILLIAM O. FIELD, JR.'S revisit to Glacier Bay during the summer of 1941 revealed, in general, widespread diminution of glacier-ice since his last visit in 1935. Nearly all the glaciers had receded considerably, and comparison with photographs taken in 1935 showed an appreciable reduction in the thickness of the ice and even its entire disappearance over large areas of moderate elevation. Yet, two glaciers--the Grand Pacific and the Johns Hopkins--had advanced somewhat, as they had also prior to 1935.

It is significant that both of those glaciers are fed in large part by tributaries originating on the Fairweather Range at altitudes of 8,000 to 15,000 feet, whereas the glaciers that are so extensively wasting away have their sources on mountains only 4,000 to 7,000 feet in altitude. It seems entirely possible that the explanation is to be found in a recent upward shift of the zone of maximum snow-precipitation due to warmer conditions at the lower levels--the same cause that was suggested by KENNETH N. PHILLIPS in explanation of the rapid wasting of the lower Nisqually Glacier while its upper course not only maintains its usual volume but at times even shows an increase in thickness. In any event, during the past decade the glaciers in the Glacier Bay Region originating on lofty peaks appear to have been better nourished than previously while the glaciers originating on relatively low mountains have been decidedly undernourished.

The following notes are based on Mr. FIELD'S preliminary report:

Wood Glacier, at the head of Geikie Inlet, in 1941 had dwindled to a partly stagnant mass only a fraction of a square mile in extent and hardly more than 200 feet thick. It appears to be "in the last stages of decay," and may vanish entirely within a few years.

Geikie Glacier, which drains into the northwest arm of Geikie Inlet, had receded about 500 feet from its position in 1935. Not only the lower portion of the ice-stream but even its tributaries at altitudes of 2,500 feet and over showed considerable reduction in thickness.

Charpentier Glacier had receded several hundred feet from the point which it had reached in 1935, and, like the Geikie Glacier had suffered considerable reduction in thickness. The ice-tongue which it formerly sent southward into Geikie Inlet now appears to be cut off from the main glacier.

Maynard Glacier, which occupies the next valley to the northwest of the Charpentier, also had receded and shrunk.

Hugh Miller Glacier had receded and shrunk by amounts comparable to those of the preceding glaciers. In spite of further recession, it is now, curiously, once more a tidal glacier. The explanation is that large quantities of moraine-covered ice that encumbered the outwash plain in 1935 have melted away, leaving a depression that is now a tidal lake.

All of the glaciers mentioned have their sources in mountains between 5,000 and 5,500 feet in altitude. Some of their névé-fields lie at altitudes of less than 4,500 feet. All have been shrinking since they were first observed in the early 1890's.

Reid Glacier is in another category, being fed by the vast intermontane ice-field known as Brady Glacier. It has been receding rapidly ever since 1926. In that year its terminus already lay about 1,000 feet back of the point which it reached in 1889. By 1929 it had receded another 1,000 feet; between 1929 and 1935 about 2,500 feet more; and between 1935 and 1941 about 5,000 feet more. This shortening has been accompanied by a considerable decrease in width and thickness. Very probably this remarkable reduction of the Reid Glacier is due to a progressive lowering of the surface of the Brady ice-field.

Lamplugh Glacier, which is the main northern outlet of the Brady ice-field and doubtless occupies a much deeper valley than the Reid Glacier, has long been known as one of the most stable ice-streams in the Glacier Bay Region. However, between 1935 and 1941 its terminus receded at different points from 1,850 to 2,575 feet--another fact indicating that the great Brady ice-field is suffering an appreciable reduction in thickness.

Johns Hopkins Glacier, in marked contrast to the foregoing glaciers, has been advancing ever since 1929. That apparently anomalous behavior is, however, as already stated, very probably explained by the fact that its sources lie in the névé-fields of the Fairweather Range, at altitudes well above 8,000 feet. Among the great peaks that contribute avalanched snow to the numerous feeders of the Johns Hopkins Glacier are Mount Salisbury (12,080 feet), Lituya Peak (11,750 feet), and Mount Crillon (12,728 feet).

From 1925 to 1935 the central part of the ice-front advanced 1,450 feet, and from 1935 to 1941 it advanced 400 feet more. Though the latter advance seems relatively moderate, it added a far greater acreage of ice to the extent of the glacier than did the former advance, owing to the broadening of the ice-front.

Another, earlier event in the glacier's history is more difficult to explain. Shortly before 1926, writes Mr. FIELD, the lower end of the glacier disappeared and the terminus receded 4.85 miles from the position which it had in 1907, when it was mapped by the International Boundary Commission.

Minor glaciers of Johns Hopkins Fiord--A number of small glaciers cling to the mountains that flank Johns Hopkins Fiord below the terminus of the great trunk-glacier. These mountains are intermediate in altitude between the high peaks of the Fairweather Range and the low mountains to the east of the Brady Glacier, and, as might be expected, the behavior of the glaciers on them has been rather varied. Previous to 1935 some of these glaciers had advanced somewhat, but since then all have experienced a moderate reduction in length and/or in volume.

Margerie Glacier, whose sources are on Mount Root (12,860 feet), Mount Quincy Adams (13,560 feet), and Mount Fairweather (15,300 feet), has changed less in the last 30 years than any of the large glaciers of the Glacier Bay Region. Its terminus still is at the mouth of its valley, where it was left hanging sometime between 1907 and 1912, when the Grand Pacific Glacier retreated up to the head of Tarr Inlet, in the vicinity of the International Boundary Line.

Grand Pacific Glacier, the great trunk-glacier which discharges into Tarr Inlet, at the extreme head of the Glacier Bay fiord-system, from 1935 to 1941 advanced at its western margin, pushing to within 500 feet of the Canadian Boundary-line. The glacier has had a varied history, alternately advancing and retreating across the Boundary-line. It is now still wholly in Canadian territory. Its behavior doubtless is greatly influenced by that of its tributary, the Ferris Glacier, which heads on the Fairweather Range.

Rendu Glacier has retreated and advanced in alternation ever since 1892, when its front was mapped by Professor HARRY FIELDING REID. Prior to 1926 the glacier was receding, but some time after that year it began to advance, and by 1935 its terminus had reached a forward position similar to that of 1892. During the last six years, however, the glacier has been in recession and has been considerably reduced in thickness.

Carroll Glacier, which covers a large area to the east of Reid Arm, the upper reach of Glacier Bay, as late as 1919 came down to tidewater in Queen Inlet. By 1926, however, it no longer reached the water, and since then its lower end has shrunk--more by lowering of the surface than by recession of the terminus.

Muir Glacier is continuing to retreat at a rapid rate "and now furnishes perhaps the most spectacular example of glacier shrinkage on this continent in recent decades" [15, p. 154]. Its terminus has receded three miles since 1929 and is now some 12 miles back from its location in the late 1890's. It is discharging icebergs on a large scale.

Adams Glacier, which formerly was tributary to the Muir Glacier, and in 1931 still covered about 20 square miles of country, now has almost disappeared. In its place there is a large tidal inlet. Mr. FIELD and his party made a topographic map of Muir Inlet, the lower part of the Muir Glacier, the Plateau Glacier, the Cushing Plateau, and the country adjoining Muir Inlet on the east, in order to show the extensive changes that have taken place in the extent of the ice in recent years.

A visit to the fiord region southeast of Juneau revealed that in Taku Inlet the Norris Glacier and the Twin Glaciers were still receding, while the Taku and its distributary ice-tongue, the Hole-in-the-wall Glacier, were advancing. Triangulation-measurements show that different parts of the broad terminus of the Taku are now from 600 to 2,750 feet more advanced than they were in 1937. Since 1890 the Taku has advanced a distance of more than three miles. Its terminus now rests largely on an exposed bar in a place where the water was more than 40 fathoms deep in 1890.

In Tracy Arm, Sawyer Glacier had receded somewhat since 1935, while South Sawyer Glacier had remained unchanged. By triangulation it was determined that since the fiord was first mapped in 1889 Sawyer Glacier has made a net recession of 1/2 mile and South Sawyer Glacier one ranging from 1/2 to 3/4 mile. The lower portion of Sumdum Glacier appeared to have shrunk in volume since 1935.

At the head of Fords Terror, Brown Glacier and South Brown Glacier continue to recede and shrink in volume. North Dawes Glacier also is receding and is now more than 4,000 feet from tidewater. Dawes Glacier, on the other hand, appears unchanged since 1935. Triangulation showed that since 1889 this glacier has retreated a net distance of 3,000 to 4,000 feet.

Baird Glacier, in Thomas Bay, remains in the advancing class. Since 1924 it has advanced a net distance of several hundred feet, and since 1887 fully 2,500 feet. On the other hand, Patterson Glacier, in the same bay, is receding. Its terminus has withdrawn a distance of about 2,000 feet from the position it occupied in the 1890's.

Mr. FIELD summarizes the situation in southeastern Alaska by saying that, in general, the lesser glaciers and the lower ice-fields appear to have shrunk rapidly in recent years, while the large trunk glaciers have behaved in various ways. The Taku and Baird "have recently been plowing into mature forests, an indication that they are as far advanced as at any time in perhaps 500 years" [15, p. 155]. The Patterson, Dawes, South Sawyer, Twin, and Norris have receded perhaps not more than a mile or two from the farthermost limits they have attained in the last 100 years--in contrast to the ice in the Glacier Bay Region, which in the last 150 years has melted back 35 miles, as measured to the front of the Muir Glacier, and 57 miles, as measured to the front of the Grand Pacific Glacier.

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U. S. Geological Survey,
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REPORT OF COMMITTEE ON SNOW, 1941-42

J. E. Church, Chairman
(Presented in abstract by François E. Matthes)

The field

Inevitably and desirably the field of the Committee on Snow is widening with the times and the needs. The hydrology of snow has now become the human side of snow and snow-survey conferences have become snow-conferences. Ice is merged with snow in the consciousness of both layman and scientist but retains its identity in the American Geophysical Union in its special manifestation as glaciers and ice-caps.

Although all fields in snow stretch imperceptibly from pure science to human use, the Committee seeks only to study fundamental principles and to urge their application. Thus it plans to emphasize the scientific view and yet develop the human touch.

Since one-fourth to one-third of the land-surface of the Earth has a seasonal snow-cover, according to R. E. HORTON, the field is broad and its aspect varied. In these days too when the unity of the world is becoming obvious the geographical field also should be expanded. Furthermore, while opportunity for research is being temporarily contracted, the Committees of the American Geophysical Union by inspiring and publishing the fruits of research should keep the membership conscious of its vitality and purpose.

Personnel

The personnel of the Committee has been increased by the addition of Dr. RALPH L. BELKNAP, who has wintered and summered in Greenland and is meteorologist at the University of Michigan.

The season of 1941-42

So far as the season and reports reveal, the snow-cover for the winter in the far eastern States was somewhat below normal and spotted. The storage-reserves were low, but the snow-cover was unmelted. The Central States had an open winter with melting. In the western States the snow-cover approached its seasonal normal one month early with excellent soil-moisture and reservoirs practically full. Last summer both Boulder Dam on the Colorado and Roosevelt Dam on the Gila held capacity-storage and in March, 1942, Lake Tahoe was drawn down to provide storage for the snow-cover, thus duplicating the conditions that caused the original development of snow-surveying.

In lowland California in March, 1942, snow covered the ground amid the palm trees in Sacramento and the hills east of San Francisco Bay. In Hawaii in mid-February on Mauna Loa and Mauna Kea, peaks over 13,000 feet in elevation, the snow covered the upper fourth of their slopes.

In Europe abnormal cold prevailed throughout the Continent in January with heavy snow in southern Italy. In February and early March enormous snows occurred in England and Scotland. Hitler paid tribute to the severity of the winter weather in Russia.

Regional reports

Detailed reports are fewer than usual but comprehensive. They are arranged from the far eastern to the western States and the corresponding Provinces of Canada.

Newfoundland (ERIC HINTON)--The Snow-Survey of the Deer Lake Hydro-Electric Development for 1942 was conducted in the same manner as last year. The main body of Grand Lake being again free of ice, the survey-party was transported by one of the small Diesel tugs. This is the fifth winter, since 1926, that Grand Lake has been navigable. Transportation upon Sandy Lake was accomplished by dog-team, as usual.

The condition of the snow was very favorable, for it was almost firm enough to walk upon without snow-shoes. Moreover, in the absence of the usual ice-crusts within the snow-blanket, it was frequently possible to gather the sample in one core.

The comparison of current data with that of former years indicates that the snow-cover is somewhat above average, and that it is from four to five per cent greater than the figures for 1931.

In view of the cold winter it is expected that the flood will commence between April 1 and 10, and will continue at moderate intensity until May 31.

The data indicate that there is ample water to maintain full power-output (112,000 kw) from now until July, 1942, at least. The computation of "Hydrological conditions at Grand Lake" shows that we may expect the reservoir to be filled. Since the flood-forecast usually underestimates the actual flood, it is possible that some spilling may be necessary. It is evident, however, that no spilling should occur until the reservoir is full.

New England (PAUL L. BEAN)--Precipitation in this area for the water-year 1941-42 to date (March 4, 1942) is slightly below the average. Temperatures average several degrees higher than in the winter of 1940-41. The pattern of the weather is not markedly different from last year, although a slight improvement is noted over last year. The valley is still subjected to near-drouth conditions.

The main river is closed by an ice-cover averaging 18-inch thickness which on even date is increasing very slowly. It is a potential source of danger in the event of an early spring break, accompanied by prolonged high temperatures and heavy rains.

The snow-cover at the headwaters of the Androscoggin near the International Boundary averages from 72 inches to 84 inches in depth and is considered unusually heavy. This applies to elevations above 2,500 feet (mean-sea-level datum).

The snow-cover between elevations 1,500 and 2,500 feet varies from 37 inches in depth with a water-content of nine inches at the higher elevations, to 27 inches in depth containing 6.5 inches of water at the lower elevations.

From elevations 800 to 1,500 feet, we have 30 inches of snow, containing seven inches of water at the higher elevations and 24 inches of snow, containing six inches of water at the lower elevations.

At the lower elevations between sea-level and 800 feet we have 12 inches of snow, containing four inches of water, and at the higher elevations 21 inches of snow, containing about five inches of water. The above depths of snow and water-content are average figures.

At the extreme headwaters the snow is not compacted to any considerable degree above elevation of 2,500 feet. Below 2,500-foot elevation the snow-cover is compacted coarse and granular, with a temperature averaging about 28°F. Condition of snow-cover favors an early break, increasingly with decrease in elevation.

The forest floor is frozen solid throughout the area. This is unusual, especially in respect to the depth to which the frost has generally penetrated. It is estimated as 12 inches. Normally it is not more than six inches when it occurs, which is seldom.

Heavy spring floods are not indicated as of even date. However, the winter conditions still hold in this area.

Storage-reserves in this area and in this State are very low and much more than average conditions of precipitation for March, April, and May, and until the forest-growth starts, are needed, if even satisfactory fills are to be obtained this spring.

Conditions prevailing throughout the State are not widely different from those outlined herein for the Androscoggin Basin.

In spite of war conditions, we are carrying on the snow-surveys as usual, but not enlarging the traverses or setting up new ones. Study of snow-characteristics is not being developed this year as much as in former years.

Some rather typical snow-measurements have been received April 6, 1942, which are as follows: On March 11 in the White Mountains at Pinkham Notch, elevation approximately 1,800 feet, 36 inches of snow, with 10.8-inch water-content and density 30. On March 25 at Kennebago, elevation 1800 feet, 48 inches of snow with 14.7-inch water-content. At Bemis, which is on high land overlooking the lake, 50 inches of snow with 14-inch water-content.

On April 6, 1942, the snow-cover has not begun to melt, but the above typical readings indicate about as heavy a water-content as we have ever had, with the possible exception of the year 1936. However, I think our flood-danger is small, because practically all the ice has left the lower reaches of the river.

New England (HENRY I. BALDWIN)--No noteworthy matters can be reported. Snow-cover during the winter 1941-42 has been about normal, but irregular in distribution. The ground was bare in many parts of New England during January and small forest-fires were reported in New Hampshire. During February snows accumulated rapidly at higher elevations and in the north, but at many points in the Connecticut and Lake Champlain valleys bare ground persisted. Central and eastern Massachusetts had little or no snow most of the winter. The accumulation on March 10, 1942, seems unlikely to produce destructive floods from normal melting alone.

Skiing continues to be a major activity in many parts of northern New England, and war restrictions do not seem to have yet affected the numbers visiting ski-resorts. Work of the National Ski Patrol is especially to be commended.

Lumbering and pulpwood operations have been at a maximum this winter. There are upwards of 400 portable sawmills (more than ever before in history) registered in New Hampshire alone,

and the cut of both hardwood and softwood pulpwood is at a record figure. Snow has a very important influence on woods operations in New England; now that motor trucking plays a vital part in moving products, too much snow can be a serious obstacle, just as too little may retard woods operations. Nearly all lumber cut by portable mills is carried to market by motor truck.

Michigan (W. U. GARSTKA)--The winter at East Lansing has been an open one for the most part to February 7, 1942. We have had just one snow-storm, which was really a combination of rain and snow resulting in a shallow accumulation of high-density snow. Within less than a week's time we have experienced temperatures of -6° and also several degrees above freezing, so that runoff occurred at the cultivated watersheds. These periodic thaws give us an opportunity to observe hydrology under winter conditions several times in the course of a single winter season. This would not be the case if the project had been located somewhere further north.

North Continental Divide: Bow River, Alberta (P. A. FETTERLY and O. H. HOOVER)--On the basis of eight snow-courses in the vicinity of Lake Louise it is estimated that the Bow River at Banff for the period April to July may discharge approximately 500,000 acre-feet, which is about 91 per cent of the previous five-year average or 82 per cent of the long-term mean.

Past experience however reveals that this forecast can be materially disturbed by rains in June or July, which often have contributed so materially to the floods on the Bow River.

North Continental Divide: Missouri Headwaters Region (D. B. FREEMAN)--Snow-surveys made by the United States Geological Survey for the Army Engineers during the early part of March, 1942, indicated an average snow-cover for the headwaters-region of the Missouri River of approximately 35 inches, with a mean water-content of approximately nine inches. This latter figure is about average for the previous period of snow-survey record, 1935-41, for March 1.

Rain which fell in the fall of 1941 has primed the soil for favorable runoff-conditions. If the spring and summer precipitation is average or above, the runoff for March to July, 1942, for the Missouri headwaters-region should considerably exceed the runoff for this five-month period for either 1940 or 1941.

North Continental Divide: Fort Peck Dam--According to the March 1942 issue of Reclamation Era, Fort Peck Dam, biggest in the world--128,000,000 cubic yards of earthfill--has been storing Missouri waters after releasing them in the summer of 1941 to maintain a navigable depth of six feet on the lower Missouri. The reservoir waters were 12 feet deep at the beginning of the year and rising. Fort Peck's Reservoir is the longest--189 miles--in the country and covers the largest surface-area--245,000 acres. Storage-volume falls short of Lake Mead's at Boulder Dam, however, with 19,000,000 acre-feet compared to 32,359,274.

North Continental Divide: Columbia River (S. H. FRAME)--The average water-content of the snow, April 1, 1942, at 12 snow-courses varying in elevation from 1,800 feet to 4,500 feet is 14 per cent above that of last year. The runoff at Golden is estimated at 74 per cent of average or about 1,558,000 acre-feet; 61 per cent at Revelstoke, or approximately 10,944,000 acre-feet; and at Trail 67 per cent or in the vicinity of 23,612,000 acre-feet. A 28-year average has been obtained for the Columbia at Golden, Revelstoke, and Trail for the period April 1 to August 31.

This year (1941-42) the ground at many of the snow-courses at lower elevations was frozen and at higher altitudes this was the case at practically all courses. This condition will tend to quickly fill any depleted reservoirs and, with the soil containing a considerable amount of moisture, the runoff should be fairly well sustained throughout the period April to August. The foregoing forecasts for the different areas mentioned should be only taken as a general trend of what may be expected.

North Continental Divide: Canada and Lower Columbia (R. A. WORK)--The supplies of water, April 1, 1942, for generating electric power in Canada and on the Lower Columbia in the states of Washington and Oregon are estimated at slightly under the runoff of 1940. According to the present demands for the energy at least a mild shortage of water is indicated for this purpose.

Grand Coulee Dam, "the biggest thing on earth," is now nearing completion. The reservoir of 151 miles in length reaching to the Canadian Boundary is now full and water (June 1, 1942) has spilled over the dam. In March, 1941, the first power was delivered to war industry and other power-units have followed. The irrigation of 1,200,000 acres will come more slowly but as surely.

South Continental Divide: Arkansas River (RALPH L. PARSHALL)--Runoff this season (1941-42) from melting snow will be about normal. Irrigated areas in the lower valley have good to excellent soil-moisture. Stream-flow is above average and reservoirs are practically all filled. The storage now is the best in years.

South Continental Divide: Rio Grande--According to Reclamation Era of September 1941, Elephant Butte Reservoir spillway has received its first literal christening after more than a quarter of a century of reservoir-operation. The lake rose 3.2 feet above the controlled spillway-crest to a record high elevation of 4399.2 feet (content of 1,937,700 acre-feet in July, 1941, and the gates were swung open for a limited release in a successful test of the spillway. Having reached this high elevation, Elephant Butte Reservoir is expected to operate at high stages for a period of several years, and the project is assured of a long-term adequate water-supply. Storage in the reservoir in July, with the water still rising, was equal to more than a two-year supply for irrigation with sufficient surplus for the generation of electrical energy in the new Elephant Butte Power Plant. The average firm energy-output from the plant is estimated at about 90,000,000 kilowatt-hours.

South Continental Divide: Rio Grande (RALPH L. PARSHALL)--Special requests are at hand (December 5, 1941) for preliminary estimates of the runoff in the Rio Grande next season. It is rather encouraging to know that we are being called upon to supply this information. We are sending out a call for snow-surveys on January 1 on a limited number of courses as a basis to guide our statements as to what is to be expected this next year. Just now from the standpoint of present conditions we are to expect normal or better runoff in the Rio Grande next spring.

On April 1, 1942, for the watershed of the Rio Grande, in Colorado and New Mexico, the recent snow-surveys on 21 courses show an average water-content of 10.0 inches as compared with 16.2 inches a year ago and 9.8 inches as the six-year average. The runoff of April to July, 1942, will be less than last year; but, if rapid melting occurs due to above-normal temperatures, high stage of the river will be reached. The present outlook does not indicate sustained high water as occurred in 1941. Elephant Butte Reservoir, on the Rio Grande, has 1,887,000 acre-feet in storage, which is at about 83 per cent of capacity. Because of the present near-full-reservoir storage, together with an expected normal summer river-flow, this season's irrigation-supply in the Rio Grande Valley is well assured.

South Continental Divide: Rio Grande--The Bureau of Reclamation, July 16, 1942, states "Greatly abnormal April precipitation increased the slightly above normal April snow-cover to 119 per cent of the preceding five-year normal by May 1, 1942. The abnormal rainfall in April at lower elevations combined with snow-melt at higher elevations in May and June resulted in Elephant Butte Reservoir reaching a record high storage-content of 2,308,000 acre-feet on June 17, 1942, with the water-surface at elevation 4409.19 feet or 2.19 feet above the uncontrolled emergency spillway-crest. The water-surface was above the emergency spillway-crest (elevation 4,407 feet) from May 27, to July 5, 1942."

South Continental Divide: Colorado River Basin (RALPH L. PARSHALL)--The water-content of the snow-cover, April 1, 1942, in percentage of the seven-year average is: Green River 93, Upper Colorado 99, San Juan River 95, main Colorado from the Green to the Virgin Rivers 112.

To aid comparison and anticipation the United States Bureau of Reclamation has furnished the following tabulation of the water-surface elevation and storage-content of Lake Mead on April 1 of each year since storage began:

Date	Elevation, feet	Storage-content, acre-feet
April 1, 1935	701.70	80,000
April 1, 1936	906.90	3,618,000
April 1, 1937	1031.00	10,066,000
April 1, 1938	1100.20	15,888,000
April 1, 1939	1158.20	22,281,000
April 1, 1940	1164.65	23,090,000
April 1, 1941	1170.35	23,827,000
April 1, 1942	1171.25	23,937,000

E. B. DEBLER of the Bureau makes note as follows regarding these data: The above elevations are not necessarily indexes of runoff and water-supply for their individual years, since the plan of operation of Lake Mead for flood-control contemplates that the reservoir will be drawn to 24,000,000 acre-feet by March 1, and to flood-control level (22,800,000 acre-feet) by April 1, if necessary, in order to provide flood-control storage-space. The extent to which the reservoir is drawn down depends largely on the winter runoff and forecasts of flood-runoff based on accumulated winter precipitation from October 1 to February 28, and March 1 snow survey records.

August 6, 1941, a total storage in Lake Mead of nearly 31,000,000 acre-feet was attained or a level slightly less than one foot below the crest of the spillway-gates. The latter were then opened to provide storage for the surplus runoff of 1942 beyond current needs for power and irrigation. The lake attained a length of 119 miles.

South Continental Divide: Colorado River Water Conservation District (F. C. MERRIELL)--It is the custom, using reports issued by the United States Division of Irrigation, to prepare specific information relating to 14 areas in Western Colorado, which are more or less natural subdivisions of the territory and for each of which such information is desirable. Accurate numerical forecasts for these areas cannot yet be made.

Predictions as to stream-flow made on April 10, 1942, are subject to modification as the season continues. The current weather greatly influences runoff, both as to the manner of its occurrence and its ultimate amount. Late summer flow, of the greatest importance to Western Colorado irrigators, is much more dependent on current weather, even that of early summer, than is generally believed. Soil-moisture, largely determined during the previous autumn, and snow-density are also important, especially in determining the probability of high flood-peaks during May and June.

The prospect of high flood-peaks, clearly indicated at the time of the report in March, is still the most important factor in the present situation. All streams will have higher peaks than during any recent years. At the same time precipitation generally has not been normal and the prospect is that late summer flows will not be as great as in 1941. Both conditions will follow from the fact that snow-density is still very low, while soil-moisture content is high. Temperatures have been somewhat below normal and the melting season is apt to be short and hot, which will increase flood-peaks.

Arizona (RALPH L. PARSHALL)--We have recently extended our work in Arizona. We have a new snow-course (December 1941) near the headwaters of Taylor Creek, in the Beaverhead Area in New Mexico, which is on the east side of the Gila Drainage-Basin.

The snow-cover this season of 1941-42 is only 74 per cent. However, last season, reports Engineering News-Record, "for the first time in 21 years water flowed over Roosevelt Dam spillways in Arizona" and all five reservoirs on the Salt River Project, of which Roosevelt Reservoir is one, reached the maximum capacity of 1,894,800 acre-feet contrasted with 22,000 acre-feet the previous year.

Although the outlook for this season's water-supply (1941-42) in the Gila and Salt rivers is not promising as based on snow-resources, streams are running in amounts only slightly less than a year ago. The aggregate storage in the main reservoirs on Salt River is 1,678,960 acre-feet, as compared with 1,684,650 acre-feet a year ago. In the San Carlos Reservoir there are 817,800 acre-feet in storage, as compared with 670,000 acre-feet last year. San Carlos now stands at five-eights its full capacity.

Utah (GEORGE D. CLYDE)--The heavy rains during the summer of 1941 materially upset the water-forecast in Utah, not so much in quantity of water that ran off, but in the need of water-supply for irrigation. I believe that the summer of 1941 in Utah was the most favorable from the standpoint of normal conditions and plant-growth of any year in the last 20, in spite of the fact that the stream-flow from most of the streams in Utah were considerably below normal. Recurring and copious rains throughout the summer made the difference.

The snow-cover this year is about normal, the reservoirs throughout the State are practically full. The water-supply, therefore, for 1942 is unusually good and it is expected there will be no serious water-shortage in the State of Utah this year.

Nevada (H. P. BOARDMAN and J. E. CHURCH)--The regulation of Lake Tahoe the present season of 1941-42 illustrates the fruition of snow-surveying that was invoked in 1910 to forecast the rise of this lake and ease tension between the lake residents and the water-users. Amity now prevails. By early forecasts of lake-rise and timely draw-off from the lake, its maximum height is being controlled within probably one-tenth of a foot of the stipulated level of 6229.1 feet above sea-level. (Final maximum 6229.01 feet.)

The Humboldt River is flowing twice that indicated by the snow-cover and Rye Patch Reservoir is overflowing for the first time since its construction and Lovelock Valley is discharging surplus irrigation-water into Humboldt Sink that has been dry for a generation.

The snow-cover is only normal but water-reserve and soil-moisture are high.

California (FRED H. PAGET)--The measurements indicate that for the Sierra Nevada as a whole the snow-pack was 95 per cent of normal on April 10, 1942.

A supply of water ample for all normal irrigation and other needs is indicated. Extremely high peak-flows from melting snows are unlikely.

Water will again flow into Tulare Lake from the Kings, Kaweah, and Tule rivers, as the unregulated discharge of these rivers during the snow-melt season promises to materially exceed the normal demands of irrigation of the districts which they supply.

Oregon (J. H. RYAN)--The unusually heavy rains of the fall and winter of 1941 left the mountainous areas of the State in unusually good condition with most of the soils holding a capacity-supply of water. The early snows were fairly heavy, and extremely cold weather in the middle of January settled and froze this snow. Early spring precipitation left much to be desired, and the month of March came close to establishing a new record for scanty precipitation over the State as a whole.

By the time of the Snow-Survey Conferences of April 1, the moisture-conditions on the lower and middle elevation-ranges were badly depleted by the continuation of freezing nights and drying winds, and in many areas the early grass was already beginning to ripen and turn color. The wheat-fields in the semi-arid regions had an unusually good supply of moisture below a foot in depth, but the surface-soil was too dry for continued good growth of grain. This condition will not greatly affect the growth of fall-sown crops but was most decidedly affecting the spring-sown grain. Since that time light showers have occurred over most of the State, and the crop-condition is improved, but the rains have not been heavy enough to do much good to the early range.

Our streams have had a sustained and rather heavy flow all during the spring without any flashy peak-floods. The snow has gone off rather fast but there is still enough left, when considered in connection with the amount of water retained in the soil, to assure normal summer flow except in some small areas. The southeastern, eastern, and northeastern portions of the State have filled or will fill their storage-reservoirs to capacity. The Central Plains Area is sure of an abundant supply of water, but the irrigated lands, supplied from the eastern drainage-area of the Cascade Range is somewhat short of water. The Rogue River Drainage-Basin is fairly well supplied with water except for one or two irrigated districts which will be short by mid-summer.

It was possible to obtain practically a complete coverage of the snow-survey stations this spring, although there was a considerable shifting of personnel, and last-minute arrangements had to be made in order to get the surveys made. Just what the future holds for us is difficult to say. A large number of the men who have been making these snow-surveys have already entered the service or are engaged in defense-activities, and the prospects are that the next few months will see a still greater shifting of personnel.

It will be our endeavor to see that the snow-survey program is carried on, but it is very probable that next spring the survey will be confined to fewer stations. The interest and demand for the information which is furnished by the surveys are greater than ever now that emphasis is being placed on production of food, and the contributing agencies have helped in every way possible to keep the surveys going during the past season. The shortage of man-power is certain to curtail the scope of the surveys, but it is expected that the key stations and those with the longer records will be maintained.

Washington--Reclamation Era of April, 1942, states "For the first time in 17 years the Okanogan (Washington) Project is unconcerned about the coming season's water-supply. Nearly 1-1/2 years of abnormal precipitation has put storage in good shape, and this winter one of the heaviest snows in years fell on the higher mountains."

The Skagit River, source of Seattle's hydroelectric power-supply and municipal scenic recreation-center, will be brought under full control by raising the height of Ross Dam, already 305 feet above bedrock and creating a canyon lake eight miles long in the otherwise almost inaccessible mountains.

British Columbia (C. E. WEBB)--Total precipitation for period October, 1941, to March, 1942, with one exception, was about average throughout the Province. The preponderance of the precipitation fell as rain, the snowfall for the period being very much below average in all districts.

The snow-pack, as reported by observers of the Dominion Water and Power Bureau on March 15, 1942, is much less than normal in the greater part of the Province. However, late snowfall in March in the coast district added appreciably to the storage there so that runoff from snow-cover for the coast streams should be very nearly normal.

Runoff as indicated by the two principal streams, the Fraser and Columbia, have been well above normal during the whole of the winter period, due principally to mild weather-conditions prevailing, and the fact that the greater part of the precipitation fell as rain. The runoff for the Fraser Drainage-Basin, as determined by the gaging-station at Hope was 136 per cent of normal, while that of the Columbia Drainage as determined by records at Trail for the same period was also 136 per cent of the long-term mean.

It is possible, due to light snow-cover throughout the interior of the Province at this time, that the peak of this year's freshet will be less than usual on the majority of streams. Although the percentages of the long-term mean for the Fraser and Columbia rivers during the whole of the

winter period were well above normal, the percentages for each month are now gradually falling. This indicates that unless altered by extraordinary weather-conditions, the runoff during the next few months will be below average.

Mexico (FRANCISCO GOMEZ-PÉREZ)--In the Annual Report of the Committee on Snow 1940-41, I saw reference to my request relative to use of melted snow from Popocatepetl and Ixtaccihuatl. Unhappily, the project has not progressed much, on account of lack of funds, although I understand that several months work was done.

Irrigation and Power--Reclamation Era states "The year 1940-41 recorded a year of intense activity by the Bureau of Reclamation. At the close of the year 28 power-plants were in operation in 17 projects with a total installed capacity of 953,962 kilowatts--an all-time high exceeding the capacity of all electric plants on the Pacific Coast in 1912.

"The West celebrated one of its finest water-years in a generation, and Reclamation contributed largely to this satisfactory condition. The 73 reservoirs in operation on Reclamation projects on June 1 contained 41.5 million acre-feet or 13,000 billion gallons of water.

"With the expansion of its irrigation- and power-activities the Bureau was serving, at the close of the fiscal year, more than 4,700,000 persons.

"The Bureau's largest construction program pushed forward on 36 projects in 14 States during the year. Of the 17 dams under construction, eight were completed, which brought to 163 the total number of dams completed by the Bureau since 1902."

Hawaii (CHARLES W. MILLER)--For the duration of the emergency about all activities of scientific nature in the Hawaiian Islands have been side-tracked.

On February 19, 1942, there was a light fall of snow on the summit of Mauna Loa (elevation 13,680 feet). The Hilo Tribune on February 20, 1942, says "Like something you see in a dream Mauna Kea (13,856 feet elevation) emerged resplendent from the thick morning mist this morning covered with a widespread mantle of snow. Early morning risers were taken by surprise as they saw the snow-covered mountain which the night before showed no hint of snow. The transformation was so sudden and so complete that it caused much interest among Hiloites. This is Mauna Kea's first big snowfall in about a year. Unlike other times when the snow is just on the summit today's snow has fallen as far down as one-fourth of the mountain slope."

Europe--The Bulletin of the American Meteorological Society gives the following notes on the winter of 1941-42 in Europe:

"Bitter cold has been sweeping southern Europe, according to an Associated Press dispatch from Berne, Switzerland, January 4, 1942, adding to the suffering of people already distressed by lack of fuel.

"In Turkey an intense cold wave has dropped the thermometer to the lowest level in 25 years. Numerous victims to the cold are reported from some Turkish regions and transportation-services have been paralyzed.

"In Italy, where the schools are closed until January 19, 1942, to conserve fuel, the people are suffering from sharp cold and unusually heavy snow-storms. In southern Italy the snow has fallen to a great depth from Taranto to Brindisi and the temperature has dropped to - 6°C.

"Famed Mount Vesuvius is covered with snow, and so are the hills around Rome. Several persons have been reported frozen to death in various parts of the country.

"From Tirana, the capital of Albania, comes reports that the entire country has been in the grip of cold for several days. In the southern region the temperature has fallen to - 10°C (or 14°F), and the snow in some sectors of the country has fallen to the unusual depth of three feet.

"Madrid reports a cold wave in the Aragon Region of Spain, with the temperature falling to - 16°C, breaking water-mains and making the supply of water difficult in many districts. Many people are reported to have been frozen to death in Spain.

"(In February and early March there were enormous snows in England and Scotland. The news from Russia has emphasized the abnormal severity of the winter.--Ed.)"

A Russian thaw was described in a bulletin of the Soviet Union as follows: "Most of these battle points are within their driest periods now (April 8, 1942) but the thawing of the snow will turn dirt roads into slush of the kind that moved an American correspondent to write on April 4: 'Imagine all the swamps you ever saw. Imagine all the muddy ditches your automobile has whizzed past. Imagine millions and millions of mudbaths. Into this mixture dump billions of tons of grayish snow and stir thoroughly, then you've got something--you've got a Russian thaw.'"

Progress

The ground already gained in snow-surveying and forecasting stream-flow is being held despite the shifting of cooperators or withdrawal for war service. The courses in the Merrimack

and Connecticut basins have been permanently established and new courses have been laid out in the Beaverhead Area, New Mexico, and in the Reese River and Baker Creek areas, Nevada. Last season R. L. PARSHALL of the Soil Conservation Service forecasted the runoff of the Rio Grande at Elephant Butte Dam so closely that special request was sent in for an early, preliminary estimate of the present season's runoff.

Research on snow-problems and conferences to make forecasting more effective are keeping pace with field-surveys.

Snow-conferences

Snow-conferences now span the Continent and include both the United States and Canada. The Eastern Snow-Conference was held at Harvard University in September 1941, the Central Conference at Michigan State College, East Lansing, in December 1941, and the Western Interstate Snow-Survey Conference at California Institute of Technology at Pasadena in January 1942. The latter was held as usual in conjunction with the Section of Hydrology of the American Geophysical Union. To bind all geophysical interests in close cooperation, General Secretary FLEMING of the Union has offered to publish the papers of all three Conferences in the Transactions of the Union without cost, providing 500 new members for the Union can be obtained by the Conferences. Although this goal seems distant, it stands as a challenge to growth.

Although research is the central activity of each Conference, age and enthusiasm determine the immediate problems. The Eastern Conference that represents a young but well developed co-operative snow-survey system is now seeking to standardize its instruments and reports. The Central Conference, just organized, seeks a snow-survey system but has enlarged the field of snow-study to include highway transportation, recreation and wild life, and forestry and agriculture.

The Western Conference with years of snow-survey data now accumulated is carefully analyzing past and present records to improve still further the accuracy of its forecasts of stream-flow.

Eastern Snow-Conference

The Eastern Snow-Conference was held at Albany, New York on September 8, 1941, with an attendance of 47. The proceedings have not been published but the mimeographed minutes can be procured from the Secretary.

The day was devoted to the presentation and full discussion of reports by the Committees on Records, Research, and Equipment and regional reports by the various cooperating agencies detailing difficulties and suggesting improvements.

Records--The Committee on Records reported that information and available data relative to accumulated snow during the season 1940-41 had been assembled and compiled by the Hydrologic Unit of the United States Weather Bureau, Albany, New York, because of the value of these records to the general public.

It was suggested that a supplement to the bulletin be issued to include type of vegetal cover, height of vegetal cover in feet, whether or not the site was sheltered or exposed, the number of samples per snow-course, and the length of the snow-course and the depth of frozen ground in inches.

Also that it was desirable on such a record to note whether the absence of an entry indicated no snow or merely that no survey was made. Furthermore that the inclusion of much additional detailed information would be advantageous to those engaged in research-work.

Information of interest to winter sports should be included.

More information is needed on the effect of frozen ground. Unpublished studies made by M. T. AUGUSTINE with the type-F infiltrometer in New York reveal that a hardwood-forest soil may have a minimum infiltration-capacity of 0.35 inch per hour when frozen to a depth of three inches.

In Black River Basin it was found that in the open the frost was dense and rendered the ground practically impervious, but in the forest-cover with frost the ground can absorb water.

Unlike the Western Interstate Snow-Survey Conference, the participating agencies in the Eastern Conference make and publish the snow-surveys in their local districts and at the time of the maximum accumulation of snow in each locality. However, it is recognized as desirable to synchronize the work as much as possible in order to make the results comparable over the entire area.

"At the close of the season, it is planned to assemble and compile the data in a summary report."

Equipment--The Committee on Equipment reported that it had not carried on any comparative tests of various tubes or determined the best tube to use.

Two new snow-tubes were presented. The Harrisburg tube by the United States Weather Bureau, being of brass and large, was too heavy to carry far and had no ledge on the inside of the cutter to retain the core. The latter defect was due to lack of tubing of proper diameter.

The snow-tube developed by the Boston Office of Army Engineers primarily for local observers has a cutter of the same diameter as the measuring tube of the standard rain-gage. The cutter has 1/16-inch shoulder inside tube and teeth shaped like rip-saw teeth 3/8 inch long. The snow-sample is melted and measured in measuring tube of standard rain-gage.

Opinion and experience with the Mount Rose snow-sampler varied as follows:

"Believed larger snow-tube will give better samples when heavy crusts are present under snow-surface."

"The large 3-1/2 inch diameter tube was hard to get to the ground. The Mount Rose tube was far more satisfactory. Scales should be read closely to the nearest 0.1 inch."

"Scale manufactured by FRIEZ was found difficult to read accurately, particularly when a high wind was blowing."

"Friez (that is, Mount Rose) tube used and by gentle rotation would cut through sub-surface crusts."

Chairman CULLINGS suggested that equipment should be standardized so results will be comparable.

Research--Since the melting of snow now holds the center of interest in snow-studies, the report of the Research-Committee by CARROLL F. MERRIAM is quoted in full.

"Although a report of this Committee is contained in the annual Transactions of the American Geophysical Union it was prepared somewhat prior to the end of the administrative year of the Eastern Snow-Conference and, therefore, could not contain a complete summary to the present date. Additional information has since been received and moreover a résumé of further needs for research should be presented to the membership at the beginning of the new season.

"At the annual meeting in Albany, Mr. WILSON of the Weather Bureau supplemented the report of the Committee with a brief statement of the principal results that he had obtained while in the West. During this time he had made hundreds of determinations of the thermal quality of snow and although the data have not been finally compiled it may be said in general that for old snow there seems to be a limit of approximately 70 per cent below which this value does not fall. This statement checks substantially the measurements that were made under rather unfavorable conditions by the Holtwood Laboratory in southern Pennsylvania where the only snow available was from old banks when most of the rest of the countryside was bare.

"On the other hand, it appears that values as low as 50 per cent may be found in new snow. This would indicate that the water that may be held by capillary attraction by snow-crystals before they begin to melt is much greater than after the cover had begun to disintegrate. Thus if the same conditions are found to be general in the East it may be concluded that freshly fallen snow may offer a greater potential flood-danger than old snow and a sufficient threat to make it worth while to pursue this subject further.

"It appears that after some experience it is possible to estimate fairly closely the result of the calorimetric measurement of the quality merely from the feel and appearance of the snow. This would indicate that if those making snow-measurements could develop judgment by actual experiment on snow which was conveniently located to a laboratory, it would be possible for them to report field-conditions sufficiently accurately for practical purposes without the trouble of making tests. At least if these men could do sufficient experimentation to recognize snow of low thermal quality they would be able to send a warning when the conditions were conducive to rapid melting.

"So far no attempt has been made to see if there is any relation between quality and density. It is hoped that a sufficient number of determinations will soon be available where at the same

time the depth of the snow and the water-content have both been noted, so that we can get some idea of the normal changes while the density increases. Should the correlation prove at all distinct, it would give a new significance to knowing the density as indicative of flood-danger.

"The main problem that is still before us, regardless of the results that have been obtained in the Western mountains, is whether in practice there is sufficient variation to make the thermal quality a factor in the production of rapid runoff and floods under Eastern conditions. Obviously we are concerned not so much with the general average as we are with the unusual circumstances which can lead to serious trouble. Therefore, it is necessary to enlist as many watchers as possible in order not to miss the exceptional conditions under which they arise. Inasmuch as the apparatus is not expensive, and available with the exception of the wide-mouth thermos bottle in almost any secondary school laboratory, this should not prove a serious deterrent to securing cooperators. The technique likewise is not too difficult for any careful experimenter, and it would seem that teachers in physics might assign this subject to those students who can be trusted to take observations of this nature. Before undertaking this work the student should read the previous memoranda of this Committee, discussing the sources of error and how they can best be eliminated. Naturally while looking for the extraordinarily low values, as well as the attending conditions which give them, we shall want to be sure that these low values are not the result of experimental error or the failure to observe the necessary precautions. One student in fact made a number of determinations, forgetting entirely to consider the water-equivalent of his calorimeter.

"A number of laboratories and educational institutions in the East have already expressed a willingness to cooperate or have reported experiments actually made as follows: United States Weather Bureau; New York University; E. S. CULLINGS, Secretary, Black River Regulating District; Holtwood Laboratory of the Pennsylvania Water and Power Company; Class in Climatology, Dr. C. F. BROOKS, Blue Hill Meteorological Observatory; Massachusetts Institute of Technology; University of Maine; Shawinigan Water and Power Company, laboratories at Shawinigan Falls and Rapide Blanche, Quebec; M. C. STEWART and secondary school nearby. Various offices of the United States Engineers have offered to do whatever is possible under the circumstances.

"The main trouble with much of the assistance that may be expected from student work is that the samples will be drawn from locations near the schools and represent city or town conditions rather than those in the field. What is needed is a means of making measurements in locations which can be easily reached from country roads. If possible it would be desirable to convert the baggage compartment of a coupé into a mobile laboratory. This plan has been found to be satisfactory even though it was necessary to carry the supply of hot water in a gallon thermos jug without means of reheating in the field. If necessary to steady or level the car to permit the use of platform scales, a bumper jack could be used. It would be desirable to provide means for reheating the water in case that the distance to be travelled were great. It should be remembered that putting boiling water into a cold jug lowers the temperature considerably so that before leaving the laboratory it would be well to raise the temperature nearly to the boiling-point either with an electric heater or else with steam. Heated water in the field could be supplied either electrically from a storage-battery or else by a plumber's torch.

"Another plan which carries out the idea of the mobile laboratory but does not require any weighing in the field is to charge a battery of thermos bottles with hot water carefully weighed before leaving the laboratory. These could be carried in a special box, each bottle with provision for a ticket on which the data could be noted. In the field the temperature of the hot water could be observed and the sample introduced, after which the temperature of the mix should be noted. Care must be taken not to do anything that would alter the tare weight before returning to the laboratory. Here the bottles could be removed one at a time to prevent any danger of confusion in the tickets and weighed to get by difference the weight of the sample. Six or more bottles could be carried into the field at a time in an automobile. The hot water may be expected to lose only about 5°F an hour and by starting out with a temperature of about 190°F, which could be boosted after the bottles were filled by live steam or electric heaters, they could be carried for a number of hours and still be sufficiently hot for use.

"Some suggestions have been made for using chemicals which would mix with snow and generate sufficient heat for melting. So far little has been done to investigate the possibilities in this line. If something satisfactory could be found, it would enable measurements to be made under field-conditions where transportation of hot water or means of heating it might be difficult.

"In addition to making actual measurements, those laboratories which have ready access to field-conditions could well devote serious study to the question of proper sampling methods. With deep snow it is obvious that the entire contents of a sampling-tube of any reasonable diameter would be too much to put into the calorimeter and, therefore, to get a representative sample it would be necessary to mix the whole and take out only what is needed for the test. Just how this mixing should be done for the best results is not known. One suggestion is to collect the whole in a large thermos jug and then withdraw what is needed after mixing. What care should be taken to be sure that the temperature of the jug is the same as that of the snow is not known. Still another

suggestion is that the jug used for collecting the sample be used as a calorimeter by putting a given amount of hot water into it rather than putting the snow into the hot water. So far little is known regarding the proper technique of testing in this manner.

"One class used an ordinary coffee can filled with snow, after which water slightly above room-temperature was added. It was reported that satisfactory results were obtained, but there are obvious disadvantages in the use of room-temperature water because the amount has to be so much greater than the weight of the sample to be melted, and therefore for the best results the weighing has to be more carefully done. It is not known whether the water-equivalent of the calorimeter was considered or not. Obviously the method used by this class should be tested with moisture-free melting ice to be sure that some error is not giving false results.

"While those laboratories that are closer to the field-conditions are engaged in actual measurement, it would seem that those in the cities could be engaged in further development in laboratory technique.

"So far most of the work has been done with wide-mouth thermos bottles, either pint or quart size. It is possible that other types of containers might be preferable such as a gallon jug as used in the early experiments at New York University.

"Some trouble has been reported in getting consistent temperature readings particularly after the mix. Means of agitating the contents should be studied to prevent stratification which must be broken up. In some experiments this has been successfully accomplished by rolling the bottle in an inclined position with sudden jerks into a vertical position at frequent intervals. The venting of the calorimeter is necessary to prevent accident, and still this must be done in such a way that there is no danger of losing any of the contents.

"Further study is needed in regard to the general procedure. There are two possibilities, either putting the snow into hot water or else putting hot water into snow. If the hot water can be boiling at the time it is injected into the calorimeter there would be no need of taking the temperature, although the barometric pressure should be noted at the time. The opening of the calorimeter to put in the sample when it contains water which is nearly at the boiling-point and when the surrounding temperature is nearly down to freezing, introduces an uncertainty as to the amount of heat thus lost. It would seem desirable to find if there were a way of avoiding this by syphoning quickly a predetermined amount of boiling water into the calorimeter when the temperatures inside and outside were not far different. Some device for boiling the water in a closed vessel provided with a vent might be made so that when the vent is closed the desired amount could be injected through an insulated tube either by blowing in through the vent or by displacement caused by the steam. It is entirely possible that when the outside temperature is not far from that of the snow a number of samples could be collected in thermos bottles and then brought to some central point for testing.

"More study is needed to investigate whether the water-equivalent of the calorimeter remains constant or whether it varies under differing conditions. Means of determining this figure should be recommended so that errors would have the best chance of offsetting each other. It appears that if the water-equivalent is determined either by using moisture-free melting ice, or else by mixing two lots of water in such a way that the observed temperatures are the same or approximately the same as in actual use, then thermometer-errors are cancelled. Should it be found that errors in individual thermometers are sufficient to make appreciable differences in the final results, it can be concluded that only one thermometer should be used and in case that is broken the water-equivalent of the calorimeter should be redetermined before making further tests.

"More information is needed regarding the proper method of waterproofing the stopper of the calorimeter.

"Some thermometers are calibrated to read correctly only when the entire mercury-column is exposed to the temperature to be read, whereas others are intended to be immersed for a given distance, the stem being at room-temperature. Such thermometers are always in error when the ambient temperature is not the same as that for which they are designed. At the same time some experimenters have felt that it is bad practice to keep slipping the thermometer in and out of the cork in order that only the top of the mercury-column should just be seen, but unless this is done there is always error particularly at the higher temperatures, the error varying with the square of the difference between the reading and the room-temperatures. Near the boiling-point this becomes quite appreciable. Consequently it will be seen that standards of good technique should be studied and recommended in practice.

"There are two alternatives to weighing on platform balances. One is to determine the quantities by volume, and this method has been used quite successfully by the Weather Bureau. In many respects it is more convenient than weighing in the field. Care must be taken to allow for the small amount of water that will remain in the calorimeter after emptying, and also when using a glass graduate at higher temperatures there is an appreciable correction to make. One objection to the use of a graduate for measuring the amount of hot water is that there is an additional reduction in temperature caused by pouring the hot water into a cold container. There is no error which results from the loss of heat, but anything that reduces the temperature-range between that

of the hot water and that of the mix is undesirable. There is, however, no reason why the water could not be reheated after it was in the graduate. The second alternative is to use a spring-balance, but so far no experiments have come to our attention in which this was used. It would be rather difficult to get anything that would be satisfactory for small samples, although if a gallon jug were used and the test made on a larger scale it is possible that the scales used for weighing the sampling-tube might prove satisfactory.

"There is likewise need for more fundamental study of the history of snow-melt. To some extent a heavy snow-cover may delay runoff by absorbing a limited amount of rain, whereas should the capacity for absorption be already taken up, the rate of runoff may be greatly increased by the melting of the crystals that hold a storage of water. It would seem possible that measurements could be made on concrete slabs slightly pitched so that the runoff from an impervious surface could be measured. Accelerated tests might be made on flat roofs which could be arranged for a continuous record of the discharge from the downspout.

"This suggests that measurements of the differences in total heat of snow-cover on roofs might be used as a measure of insulating value of various materials.

"Before the thermodynamic processes involved in melting snow can be thoroughly understood it is necessary that rather precise measurements be made of the changing thermal quality of the snow-cover. This may prove to be the key by which quantitative measurements of various factors may be determined. There is much to be done in the field of pure research which is possible provided that accurate measurements of the total heat of the snow-cover can be made.

"So far the Committee has not concerned itself with the field of instruments, which seems most properly to come within the scope of the Committee on Instruments. Nevertheless it is recommended that some experimental work be done on comparative results from sampling-tubes of differing sizes, and the development of the most practical equipment for the Eastern conditions where heavy accumulations are not common.

"It has been suggested that where the cover is light so that the weight of the tube is great as compared with the weight of the sample, the tube may be filled several times and emptied into a light pan for weighing. In this way a sizable amount of snow can be accumulated in proportion to the tare weight of the container, and consequently the accuracy would be improved.

"Another fruitful field for investigation would be to compare surveys made immediately before and after snow-storms with the recorded precipitation. This subject was not discussed at the last annual meeting, and it would seem pertinent to see how closely measurements of water-content on the ground would compare with gages which are depended upon to measure the additions to the snow-mantle.

"The feeling was expressed at the last meeting that the research considered by the Committee should now be expanded beyond the problem of thermal quality to which it has been confined so far. Care must be taken in such an extended program to see that anything done by the Eastern Conference will be coordinated with the programs of the others, but the point is well taken that we shall not have a complete picture of the situation until we extend our observations beyond merely noting the depth and the water-content of the snow.

"The most natural direction to turn for supplementary information is to ground-water, and it may be said definitely that effort should now be made to review the situation and see not only what observations are at present being made, but how these can be coordinated. Studies in the Susquehanna Basin have shown that there are two grave dangers which must be avoided. The first is the inclusion in the average of gages that have little or no significance in indicating the general rise and fall of the water-table. The wells which fail to conform with the others should be dropped from further consideration. The other pitfall arises from the fact that some wells are very active and vary widely in their readings from time to time, whereas others do not. Some have distinct peculiarities with respect to the average of the others, while a number have been found to attain apparently a ceiling above which they rise very reluctantly, and consequently become very insensitive to general changes in conditions in the upper ranges.

"It has been shown that while the mere averaging of readings from a number of different wells may prove a satisfactory way of showing whether the general level is rising or falling, nevertheless the averages may be greatly affected by the combination of wells that happen to be used at any given time. Consequently consistent results cannot be expected from year to year, a very important matter if the index so derived is to be used to show the relative condition of the soil from year to year.

"To meet this problem all of the observations should be assembled in one common center, as it is useless for different agencies to attempt to determine ground-water indices independently. Some bureau must be found which will undertake the task of collecting all of the data and carrying through a scientific analysis, first to eliminate the misleading wells and second to determine among those that conform to the general pattern the individual ratings or relationships between them and the average of the rest. When these rating-curves are once determined, then it is possible to reduce all observations to a common standard and when thus resolved the average may be struck with some assurance that consistent results will be had from year to year.

"Effort in this line is now just at the beginning stage and with wise planning and thorough co-operation a good foundation may be laid. The first step is to see to what extent ground-water observations are at present being taken, and thus find the deficiencies which should be made up by further search for abandoned wells in the areas that are not adequately covered. It is possible that many of the cooperating agencies of the Conference are already observing at points which are not reported to the Ground Water Division of the United States Geological Survey.

"It seems well worth while that renewed effort should be given to this subject, not only as a supplement to the snow-surveys but also because certain studies already begun by R. E. HORTON indicate that there is a rather definite relation between the ground-water height and the base-flow of rivers which may be depended upon even without further rainfall. Just what light this study will throw on those phases of the hydrologic cycle of which we know too little is a question, but the indications are that the importance of further knowledge is so great that it is well worth the attempt.

"Another element in the production of floods is the temperature of the rain,which is not usually measured. The amount of snow that can be melted by rain is governed not only by the thermal quality or latent heat of the snow, but also by the number of degrees that the rain as it actually strikes the snow is above the freezing-temperature. Small differences in temperature may alter considerably the rate of melting and the assumption that the temperature of the rain is the same as the temperature of the air at ground-level may not be a safe assumption at all. It would seem desirable to experiment with some sort of a funnel which would collect rain, and concentrate it quickly around the bulb of a thermometer, and thus measure the temperature as it strikes.

"Undoubtedly many other fields of research may occur to the members of the Conference and it is hoped that suggestions will be forthcoming so that this Committee, which began its work entirely de novo without any knowledge of the field that could best be covered, will be able to pass along to the succeeding Committee a clearer idea of the problems which appear to be the most important in advancing our knowledge of snow."

Further plans--Correspondence had with Mr. MERRIAM since his election as Chairman of the Eastern Conference reveals still wider plans for this organization and suggestions for the continued expansion of the field of the Committee on Snow of the American Geophysical Union. He writes:

"At the annual meeting of the Eastern Snow-Conference I was asked to assume the chairmanship of the Conference for this coming year and ever since that time I have been giving some study to the means by which the organization might be of greater benefit to the participating agencies. The problem of getting a base-map for plotting the observations seems to me to be one of the first to be solved and I am experimenting a little with the established military grid to see whether this cannot be adapted to our purpose. This would have the advantage of being able to convert readily from longitude and latitude to rectangular coordinates which would permit additions to be made to the map simply by giving the coordinates of the new points. Furthermore, these coordinates can be expressed as a six-digit number which would serve as positive identification for the station and also give a logical numerical order for reporting and keeping of record.

"Another possibility of strengthening the work is the development of normal curves of water-equivalent against time of the year so that it will be possible to tell as each report is received how the accumulation compares with past years. I feel that this is rather essential in the East where snow-surveys are so new that inches do not have any definite significance, and will not have until we learn better how to interpret them in terms of the probable yield in stream-flow. At present we have advanced only to the stage where we must judge the meaning of the snow-surveys in terms of the normal."

Commenting upon J. E. CHURCH'S Report on Snow, Mr. MERRIAM has submitted the following remarks:

"In order to attempt to see the picture of snow as a whole, that is to say to get something of the perspective that you have, I have been reading your Report on Snow in the Transactions of the American Geophysical Union and making notes on the same.

"So far the recreation problem has been handled entirely outside of the activities of the Conference, although we count as members representatives from several of the railroad companies.

"There has been an urge for collateral observations of ground-water and frost. I have studies on ground-water under way, but I must ask Mr. BEAN for advice on the subject of frost.

"The Report included a number of interesting regional reports. Pennsylvania would now make an additional region and I would suggest asking the Federal State Flood Control Bureau in Harrisburg under the direction of L. F. CONOVER for a report. At a meeting of the Pennsylvania Electric Association it was urged that snow-surveys be instituted south of the New York Line. When the time came, this office of Mr. CONOVER'S established well over a hundred measuring points.

"I shall send shortly a map showing the distribution of the 700 to 800 points in this northeastern district. I notice that Mr. BEAN urges inclusion of Canada and I am attempting to see if

reports can come out of Canada. I know that the Shawinigan Water and Power Company is making surveys and it would be well if their reports could be included on our map.

"Apparently there is some mystery regarding the icing of a layer at the bottom of the snow-blanket. I am wondering if consideration has been given to the fact that water held in capillary suspension is actually at a pressure which is slightly lower than the surrounding environment. Consequently, even though this is slight and the effect on the melting-point of ice is extremely small, nevertheless there is opportunity for a transfer of heat so that the heat of melting of the snow-crystals at slightly higher pressure freezes the water where the pressure is just a little lower. This would cause the entire mass to weld together in a crust, even though the air- and ground-temperatures were both above freezing.

"The quoting of passages in the Report calling attention to risks of snow-load is an admirable step. I recall inspecting a theatre in Boston during my student days and finding that the door leading from a fire-escape was blocked by an accumulation of snow which had not been removed.

"It would be interesting to know how the measurement of sublimation was undertaken and what progress has been made. In our discussion at Albany this year there was considerable doubt expressed as to the apparent loss of snow that was noted in New York State this spring. It was not known whether it soaked into the ground or evaporated into the air. This led to the suggestion that we should pay more attention to the ground-water conditions.

"In the search for superlatives such as the greatest depth of snow and the maximum water-content, it would also be desirable to search for the lowest latent heat and the conditions under which it can be observed. Apparently from Mr. WILSON'S work, fresh snow can hold more liquid water than old snow. In this case very bad conditions of extremely rapid runoff might result from a fall of damp snow which remained on the ground without yielding any runoff until the storm turned to a warm rain. In this way the rate of runoff might be greatly increased as soon as the matrix of snow holding the mass together let go.

"Inasmuch as the Report goes into many and diverse phases of ice and snow why not persuade Captain SIBLEY to prepare a résumé of the literature on ice in relation to the operation of hydro-electric plants? This would be a subject very pertinent to the work that he is doing and I know of several sources from which he could get information. There are many interesting facts to be brought out regarding frazil ice. The climbing of ice along the shores of a lake is also interesting, and we have some spectacular photographs of the ice climbing a vertical concrete-dam at Safe Harbor as a result of ice-shove on the lake. I also know that a number of years ago compression-tests were made at McGill in order to get some idea of the maximum pressure that ice could exert at different temperatures before it became plastic. The effect of building of reservoirs on rivers in decreasing the danger of ice-jams is also interesting. We feel that years of experience have shown that the building of three power-dams on the lower Susquehanna has reduced to practically nothing the danger of ice-floods which at one time did considerable damage.

"In the matter of cooperation it would seem desirable if at least the Chairman of the three Conferences could get together at some central point, or else possibly meet at the annual meeting of the American Geophysical Union."

Officers and Committees of the Eastern Snow-Conference for 1942

Officers

Chairman: C. F. MERRIAM, Pennsylvania Water and Power Company, Lexington Building, Baltimore, Maryland

Vice-Chairman: H. B. KINNISON, U. S. Geological Survey, 945 Post Office Building, Boston, Massachusetts

Secretary: FLOYD F. LeFEVER, U. S. Geological Survey, 528 Federal Building, Albany, New York, Post Office Box 948

Committees

Executive

KARL JETTER (Chairman), Hydraulic Engineer, U. S. Engineer Office, Boston, Massachusetts

BURKE L. BIGWOOD, District Engineer, U. S. Geological Survey, 225 Capitol Building, Hartford, Connecticut

WILLIAM NOYES, Public Service Company of New Hampshire, Manchester, New Hampshire

Research

WALTER T. WILSON (Chairman), U. S. Weather Bureau, Washington, D. C.

H. M. NELSON, New England Power Service Company, Boston, Massachusetts

R. M. LEGGETTE, U. S. Geological Survey, 226 Post Office Building, Jamaica, New York

Committees of the Eastern Snow-Conference for 1942--Concluded

Records
EDWARD H. SARGENT (Chairman), Hudson River Regulating District, 11 North Pearl Street, Albany, New York
S. R. DROPPERS, New York Power and Light Corporation, Broadway, Albany, New York
W. N. MORELAND, U. S. Weather Bureau, Albany, New York

Equipment
E. S. CULLINGS (Chairman), Black River Regulating District, Watertown, New York
PAUL L. BEAN, Union Water Power Company, Lewiston, Maine
BURKE L. BIGWOOD, U. S. Geological Survey, 225 Capitol Building, Hartford, Connecticut

Central Snow-Conference

The Central Snow-Conference met at Michigan State College, East Lansing, December 11-12, 1941, with a program so large and varied that sectional meetings were both desirable and necessary.

This was the first formal meeting of this Conference which covers all States and Provinces interested in snow between the Rocky and Appalachian Mountains subject to mutual adjustment in the foot-hill areas of the two ranges. In no case, however, will there be fixed geographical boundaries or limitation in choice of projects between the three Conferences.

The number in attendance was estimated as approximately 275. Cooperation between the Conferences was informally initiated by the participation of representatives of the Eastern and Western Conferences and the American Geophysical Union in the program. Affiliation with the latter was formally requested.

The first volume of Proceedings of the Conference, covering this meeting in full detail has been published by Michigan State College. The publication was sponsored by the following: Office of Short Courses, Special Courses, and Conferences of the Michigan State College; the Meteorological Division, Air Service Branch of the Canadian Department of Transport; and the Conservation Institute of the Michigan State College, under the general executive direction of Professor R. W. TENNY, Director of Short Courses, Special Courses, and Conferences. Editorial Committee for the Proceedings consisted of A. J. CONNOR, Meteorologist, Canadian Department of Transport; E. A. FINNEY, Assistant Research Engineer, Michigan State Highway Department; W. U. GARSTKA, Soil Conservation Service; Professor L. R. A. SCHOENMANN, Director, Conservation Institute, Michigan State College; Professor R. W. TENNY, Chairman Program Committee. The program can be said to be in a large measure the achievement of W. U. GARSTKA. The volume includes seven papers on snow, five papers on snow in relation to highway transportation, eight papers on snow in relation to recreation and wild life, seven papers on snow in relation to forestry and agriculture, and five papers on cryologic hydrology. Besides there are five reports from standing Committees on Research, Equipment and Field-Methods, Measurement of Snowfall with Shielded Gages, Simple Precipitation Time Recorder, and on Records. At a banquet meeting there were two addresses, presentation of a citation to J. E. CHURCH, and three motion-pictures.

Officers and Committees of Central Snow-Conference for 1942

Officers

Chairman: M. W. KYLER, General Manager, Wisconsin Valley Improvement Company, Wausau, Wisconsin
Vice-Chairman: H. MERRILL WILLS, Department of Commerce, Weather Bureau, East Lansing, Michigan
Secretary: W. U. GARSTKA, Project Supervisor, Soil Conservation Service, U. S. Department of Agriculture, East Lansing, Michigan

Committees

Executive
A. J. CONNOR, Meteorologist, Meteorological Services, Department of Transports, 315 Bloor Street West, Toronto, Canada
W. U. GARSTKA, Project Supervisor, Soil Conservation Service, 432 Agricultural Building, East Lansing, Michigan

Executive--Concluded
F. C. CHRISTOPHERSON, U. S. Geological Survey, Department of Interior, Madison, Wisconsin
HIBBERT HILL, Northern States Power Company, Minneapolis, Minnesota

Equipment and Field Methods
C. V. YOUNGQUIST (Chairman), U. S. Geological Survey, Columbus, Ohio
A. G. CARSON, Chief Engineer, U. S. Public Service Corporation, Green Bay, Wisconsin
E. P. HOWELL, Superintendent, Defiance Division, The Toledo Edison Company, Defiance, Ohio

Records
E. W. CARLSON (Chairman), Hydrological Survey, Cincinnati, Ohio
PAUL R. SPEER, District Engineer, U. S. Geological Survey, St. Paul, Minnesota
CHAS. E. HARGER, Wisconsin Michigan Power Company, Appleton, Wisconsin

Research
C. G. BATES (Chairman), Silviculturist, Lake States Forest Experiment Station, University Farm, St. Paul, Minnesota
W. U. GARSTKA, Project Supervisor, Soil Conservation Service, U. S. Department of Agriculture, East Lansing, Michigan
W. W. HORNER, Washington University, St. Louis, Missouri
J. I. PERREY, Geological Survey, U. S. Department of Interior, Columbus, Ohio

Program
H. M. WILLS (Chairman); W. U. GARSTKA (Vice-Chairman and Program Coordinator); E. W. CARLSON; A. J. CONNOR; E. A. FINNEY, Assistant Research Engineer, Michigan State Highway Department; J. I. PERREY; L. R. A. SCHOENMANN, Director, Conservation Institute, Michigan State College, East Lansing, Michigan; C. V. YOUNGQUIST

Owing to preoccupation of cooperating organizations in war activity the plan of holding annual meetings will be deferred for the present.

Western Interstate Snow-Survey Conference

The Western Snow-Conference, which is affiliated with the Regional Sections of Hydrology and publishes its transactions jointly with them, held a dinner meeting at the California Institute of Technology at Pasadena, January 16, 1942, and considered plans for a formal meeting in Salt Lake City, Utah, on June 19, 1942, for the South Continental Divide Area in conjunction with the Pacific Division of the American Association for the Advancement of Science. The growing intensity of the war, however, caused the Executive Committees of both the Snow-Conference and the Regional Section of Hydrology to abandon the meeting. If the strain relaxes by mid-summer of 1943, the Regional Section of Hydrology for the North Pacific Coast Area and probably the Snow-Conference will hold their long-planned meeting at Oregon State College, Corvallis, in conjunction with the American Association for the Advancement of Science. The South Pacific Coast Area is the only one that holds meetings in mid-winter and independently of other organizations.

The program at Pasadena was brief since the formal program was being reserved for the Salt Lake City meeting. Because of the snow accidents of 1941, emphasis was placed on safety. The remarkable flow of the Humboldt River, Nevada, during 1940-41 was the subject of a research report. The papers and proceedings are published in full in Part I of the Transactions of the American Geophysical Union for 1942.

Officers and Committees of the Western Interstate Snow-Survey Conference

For purposes of intercommunication during the possible curtailment of meetings the list of officers is given. Elections have been deferred for the duration of the war.

The Executive Committee, FRED H. PAGET, General Chairman, is composed of members representing the four group-areas as follows:

North Continental Divide Group
O. W. MONSON (Chairman), Irrigation Engineer, Montana State College, Agricultural Experiment Station, Bozeman, Montana
LYNN CRANDALL, Watermaster, District No. 36, U. S. Geological Survey District Engineer, Idaho Falls, Idaho

North Continental Divide Group--Concluded
HARRY T. GISBORNE, in charge of Forest Protection, Northern Rocky Mountain Forest and Range Experiment Station, Missoula, Montana
JAMES C. MARR, Irrigation Engineer, Division of Irrigation, U. S. Soil Conservation Service, Boise, Idaho
WALTER E. JOHNSON, in charge of Snow Surveys in Chelan and Spokane Basins, Washington Water Power Company, Spokane, Washington

South Continental Divide Group
GEORGE D. CLYDE (Chairman), Dean of Engineering and Mechanic Arts, Utah State Agricultural College, Logan, Utah
R. L. PARSHALL, Senior Irrigation Engineer, U. S. Soil Conservation Service, Fort Collins, Colorado
HARRY L. POTTS, Water Rights Engineer, Denver Water Board, Denver, Colorado
J. CECIL ALTER, Meteorologist-in-Charge, U. S. Weather Bureau, Salt Lake City, Utah (Cincinnati, Ohio, from September 1, 1941)
ASHTON R. CODD, Hydraulic Engineer, Weather Bureau Office, Boeing Field, Portland, Oregon (transferred from Salt Lake City since election)

North Pacific Group
GEORGE G. WEST (Chairman), Chief of Hydrology Section, U. S. Army Engineers, Seattle, Washington
R. A. WORK (Acting Chairman), Associate Irrigation Engineer, Division of Irrigation, U. S. Soil Conservation Service, Medford, Oregon
R. C. FARROW, Chief Hydraulic Engineer, Water Rights Branch, Department of Lands, Victoria, British Columbia
PHIL E. CHURCH, Assistant Professor of Geography and Meteorology, University of Washington, Seattle, Washington (at present, Institute of Meteorology, University of Chicago, Chicago, Illinois)
G. H. CANFIELD, District Engineer, U. S. Geological Survey, Portland, Oregon
S. H. FRAME (Acting Member), Hydraulic Engineer, Water Rights Branch, Department of Lands, Victoria, British Columbia
NORBERT H. LEUPOLD (Acting Member), U. S. Engineers Office, 500 Pittock Block, Portland, Oregon

South Pacific Group
FRED H. PAGET (Chairman), Associate Hydraulic Engineer, Division of Water Resources, California State Department of Public Works, Sacramento, California
H. P. BOARDMAN, Professor Emeritus, Civil Engineering, University of Nevada, Reno, Nevada
JAMES E. JONES, Civil Engineer, Los Angeles Department of Water and Power, Los Angeles, California
JOSEPH KITTREDGE, JR., Professor of Forestry and Forest Ecology, Agricultural Experiment Station, University of California, Berkeley, California
W. A. LANG, Chief Hydrographer, Southern California Edison Company, Los Angeles, California

Committee on Research
J. E. CHURCH (Chairman), Nevada Agricultural Experiment Station, Reno, Nevada
GEORGE D. CLYDE, Utah State Agricultural College, Logan, Utah
R. L. PARSHALL, U. S. Soil Conservation Service, Fort Collins, Colorado
MERRILL BERNARD, U. S. Weather Bureau, Washington, D. C.
JOSEPH KITTREDGE, JR., University of California, Berkeley, California
R. A. WORK, U. S. Soil Conservation Service, Medford, Oregon

Research

Physics of snow-melt--The dominant note in research, struck by CARROLL F. MERRIAM of the Susquehanna Basin at the International Commission of Snow in 1939, is the physics of snow-melt and particularly the maximum melting rate of snow. Field-work has been actively carried on by WALTER T. WILSON under the initiative of MERRILL BERNARD of the United States Weather Bureau [Trans. Amer. Geophys. Union, 1941, Proc. Cent. Snow-Conf. 1942], and a project is under way at Crater Lake, Oregon, by R. A. WORK of the Division of Irrigation, United States Soil Conservation Service. Studies have been made by PHILLIP LIGHT of the United States Weather Bureau and FRED H. PAGET of the California Division of Water Resources. A. RUSSELL CROFT, United States Intermountain Forest and Range Experiment Station, has experimented on

the effect of dust-cover on snow on its rate of melting. The accumulation of dust on the snow in a recent year in the mountains of Utah seems to have had a material effect on its melting.

Temperature-measurements of the snow-cover (both at depth and in the zone of melting) and of the rain that falls upon the snow are essential. The Committee on Floods of the Boston Society of Civil Engineers reports that "at the present time there is apparently no proven formula for snow-melt based on thermodynamics."

The Chairman of the Committee on Snow, who has been making preliminary studies of the texture and melting of snow at the crest of the Sierra Nevada, is now planning comparative studies in the West and the East to seek climatic effects. This has been made possible by the Nevada Agricultural Experiment Station, the Division of Irrigation of the United States Soil Conservation Service, and the United States Weather Bureau, which are providing funds individually for snow-research. It is hoped that the apparent diversity in the behavior of snow will be found to be due merely to the extremes of the factors of snow and climate involved.

Two unusual years of runoff--In the Great Basin, in Nevada and Utah, heavy and recurrent rains during the period of snow-runoff in 1941 threw the forecast badly out of accuracy but have given an unexpected opportunity to determine the effect of rain in mountains and in alluvial desert soil. In the Humboldt Basin continued cold in March, 1941, and sudden and extreme rise of temperature in early April, 1941, caused another rainless flood as extreme, possibly, as that of 1910.

These unusual years of 1940-41 and 1941-42 [Trans. Amer. Geophys. Union, 1942] produced a runoff 40 to 90 per cent of normal in excess of the snow. Precipitation of double normal from April, 1941, till autumn not only increased the runoff in 1941 but raised the water-table from minimum to maximum as measured the past five years. The winter flow responded.

Superimposed upon this surface-soil, low-level snow in 1942 caused a spring flood, which in its turn saturated the soil and greatly increased the relative flow. The conditions in 1941 affected mountains and valley alike, those in 1942 affected only the valley except for some excess rain in April to May. With experience the results in 1942 could be foretold but those of 1941 could not since the continuance of the precipitation could not be foreseen.

Harmony of runoff and snow-cover on the Upper Colorado--At the initiative of F. C. MERRIELL, Secretary, Colorado River Water Conservation District, a study has been undertaken by the Nevada Agricultural Experiment Station of the harmony in relative runoff of the various sub-watersheds of the Colorado River Basin with each other and the snow-cover at the crest of the Continental Divide where most of the snow-survey courses are located. The preliminary results are reassuring.

The Colorado Basin is divided geographically into the basins of the Green, Upper Colorado, and San Juan, which provide most of the water of lower Colorado at Boulder Dam. Because of the long axis of the Continental Divide--some 760 miles--which supplies these streams, considerable diversity in the percentage of normal runoff during April to July must be expected between these three tributaries.

Studies made of the upper Colorado indicate fair harmony throughout its length. For example, in 26 years of record the maximum divergence between the head of the stream at Hot Sulphur Springs and its midway point at Glenwood Springs is 14 per cent of normal and only three years exceed ten per cent. And between Glenwood Springs and the foot of the stream at Palisade-Cameo, in 38 years of record the maximum divergence from the former is 20 per cent of normal and only five years exceed ten per cent, despite the effects of diversion.

The Yampa and the White rivers, both tributaries of the Green River but paralleling the Upper Colorado, harmonize quite well with each other for most years and fairly well with the Colorado at Glenwood Springs, though differing from the latter in a certain few years.

The Gunnison River, to the south of the Upper Colorado and joining it at Grand Junction, varies from the Colorado at Glenwood Springs more widely in per cent of normal than do the Yampa and White rivers to the north. The considerable number of years of wide divergence indicates a quite radical difference in the behavior of storms contributing to the runoff of the Gunnison and the upper portion of the Upper Colorado rivers. The evidence in Table A of the snow-surveys corroborates this:

Table A--Comparison of annual snow-cover

River	Courses	Per cent of normal						
		1936	1937	1938	1939	1940	1941	1942
Upper Colorado	6 courses, 9,700 to 11,400 ft	105	56	81	86	56	72	86
Gunnison	4 courses, 9,000 to 10,500 ft	85	68	76	54	45	69	61

The snow-surveys at the crest of the two watersheds, with the exception of 1938, 1941, and 1942, harmonize fairly with the runoff shown in Table B.

Table B--Comparison of snow-surveys and April-July runoff (per cent of normal)

Water-shed	Item	Per cent of normal						
		1936	1937	1938	1939	1940	1941	1942
(A) Upper Colorado	Snow-surveys (6 courses at 9,000 to 11,400 ft)	105	56	81	86	56	72	86
	Runoff							
	Hot Sulphur Springs	111	59	112	69	55	69.6	88.9
	Glenwood Springs	107	63	114	76	56	75.0	90.8
	Palisade	....	...	....	...	...	86	113
	Cisco (affected by Gunnison)	93	75	125	60	51	107.5	123.5
(B) Gunnison	Snow-surveys (4 courses at 9,000 to 10,500 ft)	85	68	76	54	45	69	61
	Runoff							
	Grand Junction	83	72	124	55	42	112.7	.....

The wide discrepancy between runoff and snow-cover in the Upper Colorado in 1938, 1941, and 1942, is due largely to the greater discrepancy in the Gunnison. The excess spring and summer precipitation, as measured, does not account wholly for the heavy flow.

The comparison will be extended throughout the Colorado Basin with tables covering the entire period of record as was done in the case of the Sierra Nevada watershed.

Detailed forecasts based on the snow-surveys are now being issued by the Water Conservation District for its various areas.

Interception of snow by tree-crowns--A problem long incubated by the Chairman is the evaporation of snow in tree-crowns. This should be expanded to include conifers and deciduous trees that in the Eastern mountain watersheds comprise the forest-stands in almost equal proportion. It should also be broadened to include interception.

In respect to rain, C. L. WICHT, in his "Approach to the study of rainfall interception by forest-canopies," presents the following data from a stand of poplars in Jonkershoek, South Africa: "Data of rainfall-interception and penetration in the poplar stand show that 32.27 inches of rain, or about 92.0 per cent of downpour in the open, reached the forest-floor. The penetration and interception varied greatly in amount and nature, according to whether the trees were in leaf or bare. Direct penetration and drip through trees in leaf was 79.7 per cent and through bare trees 82.1 per cent. Stem-runoff from trees in leaf was 6.1 per cent and from bare trees 14.9 per cent. Interception by trees in leaf was 14.2 per cent and by bare trees 3.0 per cent."

The interception of snow differs from that of rain in losing less of its moisture to the intercepting branches but in being longer exposed to evaporation before it reaches the ground. Sun and wind, however, though the two effective agents in evaporation, quickly cause the snow to fall to the ground. The wind particularly is effective in shaking down dry snow. The wet snow frozen to the needles or twigs is quickly melted by insolation at its points of attachment and falls. The opaqueness of the tree accelerates the melting. Only during sunless weather does the snow cling long.

The effects of snow-cover on fish-life--Snow-studies have already expanded to Wildlife Refuges where snow-surveys are now made regularly to determine snow-cover and summer water-supplies. Recently a relationship has been discovered between heavy snow-cover in the Eastern States and the winter mortality of fish. This lies in the exclusion of sunlight to water below the ice, thus hindering the generation of oxygen by aquatic plants and phytoplankton. If the fish-population is relatively large and decaying vegetation abundant, the supply of oxygen may be depleted with fatal effects to fish-life before spring. This is especially true where the lakes are shallow.

In the Western mountains where the snow is abnormally deep such mortality of fish is slight but here the lakes are deep and decaying vegetation scant.

The Michigan Institute for Fisheries Research under Dr. ALBERT S. HAZZARD is developing this problem and solving it in part by ploughing the snow-cover on the more valuable lakes into windrows and thus exposing the ice partially to sunlight.

A long list of research-problems may be found in the reports of the Research-Committees of the Snow-Conferences already given and in the Report of the Committee on Snow for 1941. Further problems are contained in the following regional reports and those on Transport and Equipment.

Newfoundland

ERIC HINTON--In accordance with recommendations, made in previous reports, twelve four-inch galvanized pipe ground-water wells were installed during October and November of 1941. Observations of the water-levels in these wells were made during the snow-survey. It is hoped that after two or three years, studies of comparative ground-water levels at the times of snow-survey will reduce errors in forecasting the flood.

It is intended to install the thermograph, now used to observe water-temperatures, at the forebay, in a suitable place to determine soil-temperatures.

New England

PAUL L. BEAN--I am all ready (December 3, 1941) for the winter snowfall and plan on carrying on as best I can, although probably we will not be able to advance in the matter of quality of the work done. I am, however, determined that there shall be no break in the record regardless of how much we may have to hold back on research-work.

"I am faced here this winter with a rather peculiar problem, owing to the drouth which we have been undergoing for the past year. The State of Maine was probably never in such poor shape in the matter of reserve storage to carry through the year. This is due to practically no rain in the months of April and May of 1941. In this area it is interesting to note, that as a result of my snow-surveys, I did obtain as much water in the lakes, and a little more, than the snow-surveys indicated, but the water-content of the snow was not enough however to provide a fill unless we received average rainfall during the months of April and May. I went through the winter operating on the basis that during the months of April and May I could rely on approximately 50 per cent of the average rainfall but, as a matter of fact, we received practically none and my failure to obtain a 100 per cent fill was almost entirely due to this drop in rainfall. Other areas in this State, which pay little attention to the water-content of the snow, are practically empty today, whereas my reserves are from 42 to 43 per cent full. Snow-surveys are the reason why I am in this relatively good condition.

Snow-surveys during the coming season will enable me so to divide the reserve on hand as to determine what flow I can deliver during the winter and still fill during the coming spring. Briefly, as we are now advancing into the winter season and I know how much ground-water I have, it is necessary for me to see that I do not use any of the snow which may melt this winter in providing flow during the winter, and, incidentally, this is the first time this condition has ever arisen and I believe snow-surveys will help me solve this problem satisfactorily.

KENNETH L. ROBERTS--Somehow I seem to be continually getting farther and farther from snow and all thoughts of water in its various solid forms. The flood-control survey of the Connecticut River is finished and it does not look as though we would be doing any more work in the northeastern snow for a while. Mr. GOODELL, who joined with me in writing the brief article on snow-measurements, is now working on a survey in Utah where they are studying some of the effects of snow on flood-runoff. At the moment I do not know of any other flood-control survey that is being conducted in a snowy part of the country

Michigan

W. U. GARSTKA--The following note on "Winter hydrology of Michigan farm lands" is published by permission of the Publications Unit of the United States Soil Conservation Service.

This project was set up by the Office of Research, Soil Conservation Service, in cooperation with the Michigan Agricultural Experiment Station to study the hydrology of farm lands with special reference to winter conditions of frozen soil and of snow-cover. The field-installations consist of two cultivated and one wooded watershed near East Lansing, Michigan. The cultivated watersheds are located on the farms of the Michigan Agricultural Experiment Station; the wooded watershed is on the lands of the Rose Lake Wildlife Experiment Station of the Michigan State Department of Conservation.

There are a number of substations at which surface-runoff is not being measured. Four such substations have already been established. These are located near Lake City, Atlanta, East Jordan, and Chatham, all in the State of Michigan.

The principal precipitation-gages (elevation 840 feet) at the wooded watershed are at latitude 42° 48′ 52″, longitude 84° 23′ 00″, in SW 1/4 of SW 1/4 Section 13, Twp. 5N, Range 1 W of the Michigan meridian. The principal precipitation-gages (elevation 888 feet) at the cultivated watersheds are at latitude 42° 42′ 08″ and longitude 84° 28′ 29″, in NE 1/4 of SW 1/4 of Section 30, Twp. 4N, Range 1 W of the Michigan meridian. The location of this project in Michigan has turned out to be an advantageous one, since the winter season at East Lansing is apt to be broken by a number of thaws, thus presenting more than one opportunity per year for the study of the peculiar hydrologic phenomena associated with winter-to-spring transition.

Table A presents a summary of the winter precipitation and runoff from the beginning of record for the past two winters. A number of articles are being prepared dealing in detail with the two seasons' observations.

Table A--Summary of winter precipitation and runoff-measurements, East Lansing, Michigan

Period	Cultivated watersheds			Wooded watersheds	
	Precipitation	Runoff area		Precipitation	Runoff, 1.65 acres
		A=1.98 acres	B=1.35 acres		
	in	in	in	in	in
Jan. 21-31, 1941	0.26	0.15	.....	.....	.....
Feb. 1941	0.15	0.66	.....	0.22[b]	None[b]
Mar. 1941	1.06	1.19	None[a]	1.12	Trace
Totals, period of record	1.47	2.00	None	1.34	Trace
Dec. 1941	1.59	None	None	1.38	None
Jan. 1942	1.73	0.37	0.17	2.07	None
Feb. 1942	0.56	0.61	0.49	0.64	None
Mar. 1942	3.26	4.17	5.71	4.91	0.79
Totals, winter season	7.14	5.15	6.37	9.00	0.79

[a] Record began March 26, 1941. [b] Record began February 13, 1941

The cultivated watershed produced sweet clover in 1940 and corn in 1941 growing seasons. The wooded watershed has a good cover of second growth oak-hickory type. The soils are Hillsdale loam and a Hillsdale-Miami complex at the cultivated and wooded sites, respectively.

During the 1941-42 winter season a number of the larger storms offered an opportunity to compare the catch of standard, Nipher shielded and recording rain-gages. The Nipher shield is of sheet-metal construction with wire splash-guard as developed at the Coshocton Experimental Watershed of the Soil Conservation Service. These data are given in Table B.

The past winter's snowfall was of such character as to preclude highly accurate application of snow-surveying technique, for two reasons. First, the snowfall was of shallow depths (the maximum single fall being 6 inches on February 2) and secondly, wind caused snow-drifts to form and to re-form, making it difficult to ascertain exactly how much water was present in storage in snow banks from day to day at any one place.

Measurement with sheet-metal flumes of runoff under winter-spring conditions of freezing at night and thawing in the daytime presents a number of problems.

Table B--Comparison of precipitation-measurement for selected storms, East Lansing, Michigan

Date	Form of precipitation	Wooded watershed			Cultivated watershed		
		Shielded[1] gage	Standard[2] gage	Recording[3] gage*	Shielded[1] gage	Standard[2] gage	Recording[4] gage*
1941-42		in	in	in	in	in	in
Nov. 6	First snow-flurries	.....	.....	.....	.....	.....	.....
Dec. 1	Rain	0.06	.....	.....	0.09	0.07	0.07
5	Rain	0.01	.....	.....	0.05	0.04	0.04
23, 24	Rain and snow (thunderstorm)	1.15	1.11	1.08	1.34	1.26	1.21
Dec. 25, 28, Jan. 1	Rain and snow	0.98	0.83	0.73	0.84	0.64	0.59
Jan. 12	Snow	0.18	0.12	0.06	0.15	0.08	0.06
18	Snow	0.06	0.04	0.03	0.03	0.01	0.01
Jan. 30-Feb. 2	Snow and sleet	1.70	1.40	1.38	1.46	1.29	1.19
Feb. 3, 4	Snow	0.07	0.10	0.05	0.09	0.06	0.03
10	Snow	0.32	0.20	0.21	0.23	0.16	0.10
15-17	Sleet and rain	0.39	0.33	0.32	0.43	0.33	0.31
Mar. 2	Snow	0.11	0.05	0.05	0.10	0.07	0.04
8	Rain and sleet	2.36	1.95	1.93	1.49	1.38	1.45
16, 17	Rain	2.50	2.35	2.31	1.49	1.46	1.44
27, 28	Rain	0.60	0.58	0.55	0.42	0.30	0.31
Total	.....	10.49	7.80	8.70	8.21	7.15	6.87

*Pail measurements, not chart-readings. [1]Standard gage with Nipher-type shield with screen. [2]Eight-inch diameter U.S. Weather Bureau standard gage. [3]Friez reconnaissance six-inch capacity gage. [4]Ferguson nine-inch capacity gage.

The ice-formation shown in Figure A is the result of a trickle-flow, building up the ice-mass shown when freezing layer upon layer. To prevent this it is necessary to heat the floor of the metal flume; preventing ice-formation in the still-well is not enough.

Fig. A--Section of ice-formation 2.9 inches thick in the throat of a Type-3H sheet-metal flume; ice nearest camera cut away to show shape of section along longitudinal axis of flume; the trickling flow which ultimately produced this ice-layer was taking place at an air-temperature of 22°F at about 4 P.M. Eastern War Time, February 17, 1942, at cultivated Watershed "A"
(Photograph by Robert A. Sanderson)

All of the winter flows resulting from snow-melt were clear and carried no erosion. Some erosion has been caused by rainfall on soil frozen at lower horizons.

Outstanding storms of the winter season of 1941-42 occurred March 8-9 and March 16-17, 1942. Precipitation (as measured in the standard gage) on March 8-9 was 1.38 inches at the cultivated watersheds and 1.88 inches at the wooded watershed, and on March 16-17 was 1.46 inches at the cultivated watersheds and 2.26 inches at the wooded watershed. The storm of March 8-9 was snow, sleet, and rain. All of the precipitation on March 16-17 was rain.

Continental Divide

G. W. MUSGRAVE--Incidental to the development of infiltration-studies by the Soil Conservation Service at Colorado Springs, Colorado, some information on snowfall was secured during the past year. Most of the precipitation at this location occurs during the summer months in the form of scattered thunder-storms of high intensity and short duration. Precipitation is generally lowest in mid-winter and occurs in the form of snow which seldom covers the land for more than a few days, being melted, evaporated, or removed into drifts by the wind. In spring and fall, "snowball"-storms sometimes occur. These consist of storms similar to thunder-showers, but with precipitation in the form of spherical snow-pellets. The pellets may approach one-half inch in diameter and have a low specific

gravity, being not nearly so dense as are hailstones and thus not doing the damage hailstones do as they fall. During these storms fields have almost the exact appearance of large pans of popping popcorn due to the bouncing of the snow-white pellets upon striking the soil-surface.

A few records were secured during the course of these studies during the past year showing the rate of snow-melt during the application of artificial rainfall. With rainfall-simulator equipment operating upon plots 6 feet by 12 feet in size, rainfall was applied in one instance at a rate of 1.6 inches per hour to a plot on which there was a natural snow-cover with a water-content of 0.36 inch. All of the rain applied for the first 15 minutes of this run was absorbed by the snow, there being no runoff and little or no infiltration during this period. At this time, the snow apparently produced a very similar effect to that of a protective vegetal cover. After the snow became wetted, infiltration and runoff began, infiltration proceeding throughout the storm at a rate of approximately 0.32 inch per hour. The snow was melted at the end of 2-1/2 hours after the start of rainfall. The temperature of the supply-water during this period was 38°F.

There are an insufficient number of cases at this time to make very definite statements as to the rate of infiltration as it may occur beneath a snow-mantle in comparison with its occurrence on the same plot without a snow-mantle. However, in the instance cited, the rate (0.32 inch per hour) is somewhat higher than the average rate in the absence of snow and it is quite possible that further evidence may indicate a higher rate of infiltration to commonly occur when the ground is covered by snow.

From this project it is anticipated further evidence will be forthcoming on the effect of snowfall on soil-temperatures, the depth of freezing, and the content of soil-moisture. It is expected, also, to develop information on the thermal relations of snow and underlying soil. Hydrographs showing the rate of precipitation, the rate of runoff, and the rate of infiltration are being secured for the various storms that occur on areas both when snow is present and when it is not, and with good data descriptive of the environment.

J. R. RITER--The Bureau of Reclamation continued in 1941 its program of financial cooperation with the Department of Agriculture in snow-survey work, but has done nothing directly in furthering snow-research. The Bureau makes independent estimates of flood-runoff on a few watersheds in the interest of reservoir-operations, but as available data on snow-surveys in the areas of greatest concern to the Bureau cover only a short period of record, no extensive analyses toward the improvement of forecasting methods have been undertaken.

Committee Cooperation

The Committees on Snow and Glaciers have long since established mutual view-points by sharing Chairmen as has been done by other closely related committees. They also share some members in common.

This year Chairman MUSGRAVE, representative of the Soil Conservation Service and the Committee on Infiltration, has generously suggested further cooperation as follows:

I think we have both at various times referred to the possibility of closer collaboration between the Committee on Snow and the Committee on Infiltration. There is so much of common interest in the two subjects that it is obviously possible for each group to contribute something to the other.

In our infiltration-work we are now in a position to evaluate fairly well the temperature-factor as it affects infiltration. At the same time we have reason to believe that frequently temperatures under a good snow-blanket are higher (and therefore more favorable to infiltration) than is the case on areas where snow is sparse or absent.

At Edwardsville, Illinois, and elsewhere we have experiments from which the runoff from natural precipitation is measured and where a valuation of infiltration for various conditions of natural precipitation is possible. At the same place, there is also work indicating the rate of snow-melt, for various conditions.

We have evidence from several of these places that infiltration does proceed beneath snow although this is a field which we have not developed as much as the importance of the subject possibly demands. Probably it is a field to which those of us working in infiltration should give more attention.

From the view-point of the Committee on Snow doubtless there is nearly as much interest in knowing how much of it infiltrates and how much of it is subject to flood-flow as in the case of the Committee on Infiltration. In our land-use studies we have found considerable differences in the amount of snow retained on the ground as well as its rate of melt on bare soils in contrast to those having different kinds of vegetal cover.

As I recall the Committee has an interest in research dealing with temperature beneath snow-blankets. This is an extremely important matter and as I recall some attention has already been given to it.

These comments are intended as more or less of an inquiry to ascertain the view-point of the Committee on Snow upon the matter and to learn whether or not there are possibilities for collaboration in furthering mutual interests simultaneously. One of the basic objectives of the Committee on Snow doubtless is to make the water available for efficient use and anything which is to make the water available for efficient use and anything which tends to increase the infiltration from melted snow is so much to the good. The objectives of course in much of our work are also those of conserving water for effective use. I have long been a believer that in research-work, team-work also can advance the projects advantageously.

To this the Chairman replied as follows:

Close collaboration between the Committees on Snow and on Infiltration is one of the inevitable developments. It should extend also to underground waters. For this reason both you and Dr. MEINZER were urged to join the International.Commission of Snow. We need now only to make the plan active. Dr. HORTON has already pioneered the way for us all.

A report from you, therefore, for the Committee on Snow regarding the results of study of infiltration from snow would be especially desirable, and since meetings may grow fewer during war times the details in the annual reports may well be made fuller. There should be included the rate of snow-melt for various conditions as they have been found. Edwardsville, Illinois, would be quite representative of the Central States, where temperatures are high and snow matures rapidly and possibly has two cycles or more during a single winter. GARSTKA is working at East Lansing, Michigan, particularly because rain and snow alternate during the winter season.

The study also of retention of snow on the ground has its counterpart in the Canadian prairies and the Dakotas where snow is being conserved by means of furrowing. There is a little world in this one project, for the conservation of snow may be beneficial to certain types of crops but may lure others to destruction. The same has been found to be true regarding potatoes. There is no use in planting them if the water-supply can not last through the period of maturity. Therefore, the ranchers want to know how much late water they can expect from the snowfields.

Your valued suggestion regarding the study of temperature beneath the snow-blanket is full of possibilities. We need to know particularly whether a snow-blanket can aid the earth-warmth in expelling frost from the ground if it once attains lodgment before heavy snowfall or whether the snow must fall before the ground has frozen.

You have spoken of one of the basic objectives of the Committee on Snow as making water available for efficient use. This was the starting point of the activity of the Committee and it wants to join forces with you. The vista, however, has been so alluring that we have gone far beyond irrigation to all of the uses and the pleasures of snow. My article "Human side of Snow: (II) Sport and transport" illustrates the heights to which pleasure can rise, and depths also perhaps. In further articles we are planning on presenting "Perennial snow and snow-peril."

Polar Regions

Although the Greenland reconnaissance of seasonal frequency of icebergs has inevitably been postponed by the war, the following comments by Dr. MAX DEMOREST will sustain interest in its details until the iceberg-census planned by Commander EDWARD H. SMITH of the Atlantic Ice Patrol can be inaugurated.

"I am particularly glad to know that you agree with my comments regarding Commander SMITH'S proposed iceberg-census, but judging from my last letter from him I fear that he is not yet persuaded to our way of thinking. He seems convinced that good observers can be found at each of the proposed stations, and that there is a considerable value to be found in daily counts. Personally I can not see that anything more than semi-monthly or even monthly counts will yield worth-while results, especially by undiscriminating observers who would not appreciate the value of considering the sizes as well as the numbers of bergs. After all, the number of bergs found on any given day at any distance from the head of an ice-fiord does not tell us how many bergs were calved on some preceding day. At best any one count can give only an approximation of the average production over a number of preceding days, for such factors as stranding and drifting must inevitably affect the discharge through a fiord.

"Probably the most significant feature to be appraised is the number of bergs of more than a given size and the relative volumes of ice found in given size-classes. Certainly the principal feature to be correlated with changing annual climatic conditions is the size of bergs calved, for I feel quite confident that the total volume of ice discharged from year to year is rather constant. Changes in total discharge would probably not be manifest except over periods of a decade or so.

"Since monthly areal photographs would contain a permanent and reliable record of all the features we desire to study I think that areal surveys should be very strongly urged. Incidentally I doubt if the cost of say five flights per season would be appreciably greater than the cost of daily counts made by unreliable natives, and in addition the flights would cover much larger areas.

Daily counts at the seven stations proposed by Commander SMITH would cost at least $5.00 a day. Over a period of five months that would come to $750 per season. I doubt if five areal flights would cost much more than this; but if they did, the increased value would be worth far more than the difference.

"You will be interested to know that LOVERING has promised to write up his material on temperature-conditions and melting at the base of glaciers. It should be a good paper and a real contribution to glaciology."

Safety

The increasing number of accidents due primarily to the increasing number of snow-mountaineers has caused the development of the National Ski Patrol and tests for ski-proficiency.

The accidents are of two kinds, namely, (a) spiral fracture due to tight ski-lashings that in a spill cause the ski to have the power of a wrench on the leg and (b) snowslides that under favorable conditions may become active menaces. Snow-surveyors have been the victims of both.

Detachable lashings are now under test but are criticised because they come loose too readily and cause emotional inconvenience or come off too late when the impact forces the leg through the crust with resulting fracture. Training and complete control are proposed by all as a compromise.

Refuge huts have unexpectedly become shelters for flyers as well as travelers by snow. W. W. McLAUGHLIN, Chief of the Division of Irrigation, suggests that charts be provided showing the location of all huts and a map be placed on the door indicating the name of the shelter and the route to nearest habitation. Toboggan and web snow-shoes to assist in hauling it should be cached in each. Two-way radio should be provided where distances are great.

Education against avalanches is now actively under way through the receipt by diplomatic pouch from Switzerland of the Swiss Avalanche Film provided by funds of individuals and organizations. The schedule already completed includes 20 appointments from the Pacific to the Atlantic and reservations have been made for the autumn of 1942. The film is being directed by the International Commission of Snow and Glaciers. Other positives in English are being planned. The present positive, whose titles are in German, French, and Italian, would thus be reserved for showing abroad after the war. It has been especially valuable for mountain troops in Switzerland and is being used here.

Detachable ski-lashings--The following study of ski-accidents by H. STEWART KIMBALL, M.D. (Sierra Club Bull., December, 1940) is quoted here as a background for further observation:

"For several years an effort has been made to study the details of ski-accidents. This study has been carried out among the members of the Sierra Club by means of a questionnaire, and it is thought appropriate, just before another season, to consider briefly a few accident-factors. Unfortunately, the complete records number only 28, and definite conclusions cannot therefore be reached on the basis of these alone.

"In answer to the question 'Does the binding allow the foot to escape when there is a powerful twist?' there were only four who said 'yes.' This is probably significant. Doubtless a binding which would release the foot when torsion is put on the ankle and knee would prevent much damage. The most common ski-injuries result from this twisting force--spiral fracture of the leg, broken ankles, sprained knees, and ankles. It was hoped that a heel-spring of the Bildstein variety would afford this safety-factor, but almost one-half of the casualties in the survey were equipped with them, indicating that such a release does not work as desired. Dr. JOEL HILDEBRAND has added this thought in recent correspondence: 'The type of release which is not yet solved is a toe-iron which would open on strong twisting pressure, less than sufficient to cause injury, but which would remain in place during ordinary skiing. This is a type of release much to be desired, and ought to constitute a challenge to inventors.'

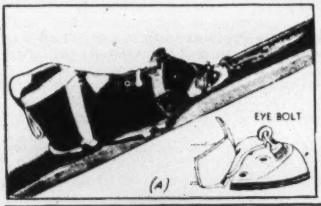
"The survey has also shown that as the day progresses, accidents become more frequent. This is due no doubt to fatigue on the part of the skier, plus changes in snow. The slope is roughened by sitzmarks, the snow may become slow in some spots, remaining icy in others, and finally, toward the close of the day, deep ruts are apt to freeze. Although most of the casualties denied that they were tired, yet as the day wears on reflexes are slowed, muscles are not so limber, and the protective mechanism of the body is more off guard. Skiing out of control and taking risks exact their toll in accidents, as does the thoughtlessness of other skiers who do not fill up their holes. Careful skiing, always in control, with careful attention to ski-etiquette, is essential for lasting enjoyment."

Two "safety lashings" have come to the Chairman's attention: the Hjalmar Hvam "Saf-ski" bindings and the "Barleau solestrap and toe-irons." Both will be given field-tests by WALTER J. HERZ to enable a detailed report next year.

The purpose and qualities of the two are expressed as follows by their manufacturers:

(a) Saf-ski--For experts and beginners; safer in downhill, steadier in slalom; tension adjustable to the strength and needs of the individual.

(b) Barieau solestrap and toe-irons (patent applied for)--There is nothing on side of ski or boot to catch snow; may be used with any type of ski; is quickly applied to any set of toe-irons; has key-binding set with skate-key to any size of foot in a moment; is definitely a cross-country and beginner's ski-binding.



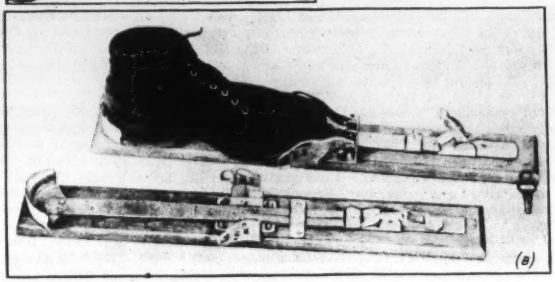


Fig. 1--(A) "Saf-ski" with adjustable eye-bolt in front retainer (to be raised for maximum tension and lowered for easy release)
(B) Barieau solestrap and toe irons (streamlined; a quick-adjusting heel strap that has no part to interfere with travel)

The following letter from JEROME E. BARIEAU sets forth the individual features of his lashings:

"Naturally I am happy to report on my ski-binding which has had three years of trial and proven ability in its use and durability. We intended to go into production this last winter in a big way but the war has postponed this effort. We have had two or three hundred out however so as to make the final changes before going into further effort.

"My binding is definitely a safe one but gets its safety-factor from the fact that there is never a strain on the foot to hold it in place. Other bindings get their control because of the fact that the toe is held with a severe pressure in the toe-irons and so something must give way in a spill. The control with my binding is because of the fact that the whole foot from heel to toe is lined with the ski and the fit in the toe-iron has nothing to do with control. There are three points of control, the heel and just one point at each side of the toe--three points. The spring in front of the toe is a light one and its give allows the foot to get in any position without a strain. The solestrap is made of clock-spring and can be bent in any form, but will come back flat to the ski after the spill. When you get out of the spill, the ski is not lost as is the case with those that release.

"My binding is definitely a cross-country and beginner's ski-binding, or a safe binding for women who do not want to go into tournament-skiing. The cable-binding with the low hitch is pretty hard to beat in tournament-work but I do have a hitch at the heel of my binding which throws out if necessary and allows the heel to rise."

Avalanches--As particularly in the Alps, there are avalanches also in America and both snow-surveyors and snow-mountaineers are trespassing on their domain. The steeper, unforested mountains are more subject to snowslides but snow if unanchored or wet may start downward on slopes as gentle as 20°.

New snow or wet snow is the chief source of avalanches and expert knowledge of both snow-texture and weather is essential to avoiding them. ROY E. LUNDQUIST, United States Weather

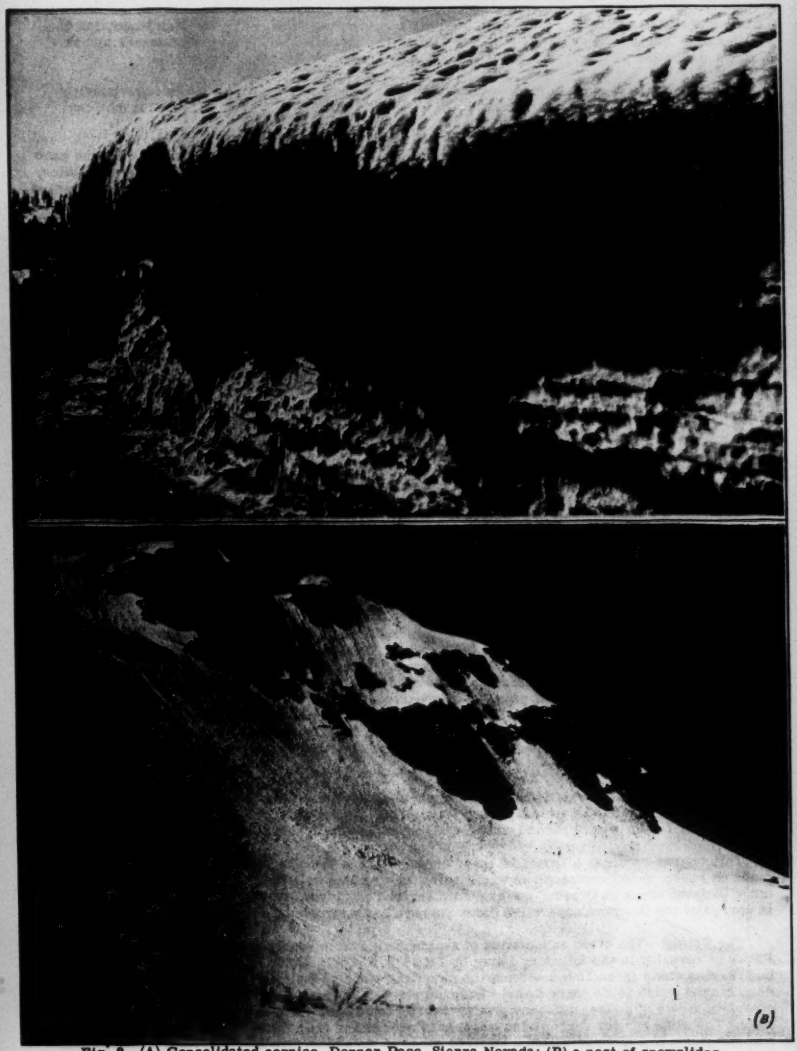


Fig. 2--(A) Consolidated cornice, Donner Pass, Sierra Nevada; (B) a nest of snowslides, Donner Pass, Sierra Nevada (Photographs by Ernest Mack)

Bureau, Salt Lake City, has analyzed snowslides and their causes in the Wasatch Mountains of Utah and a "Manual of ski mountaineering" has been prepared for snow-mountaineers and ski-troops under the editorship of DAVID R. BROWER and a committee of experts.

Observation at Donner Summit (Sierra Nevada) this past winter indicates that overhanging snow-cornices soon become consolidated but later may harbor new snow in their lee that can easily melt and slide. Figures 2-A and 2-B tell their own story.

In some cases snowslides may descend down the sides of a canyon during the day but the snow, being frozen, may be stable at night. Such is the case in Lamoille Canyon in the Ruby Mountains, Nevada, and in the Wallowa Mountains, Oregon. The area of danger should therefore be traversed in early morning before insolation becomes effective.

Marys River, Nevada--The problem of avoidance is particularly acute with snow-surveyors who must sometimes traverse avalanche-areas to reach essential snow-survey courses beyond. An example is the attainment of the headwaters of Marys River, Nevada, one of the larger tributaries of the Humboldt River.

Pinnacles and isolation make approach difficult. The avalanche-area, where the survey-party was caught in February, 1941, can be avoided by detouring up the floor of the canyon but final entrance to Marys River lies over a cirque where overhanging cornices may harbor unstable snow. The danger is accentuated by the steepness of the slope which can be reascended only by a diagonal traverse which might undercut and release the snow.

The picture is vividly sketched by TOM E. BRIERLEY, Forest Ranger: "Your letter was referred to me inasmuch as I gave considerable study to the topography and snow in West Mary's River above the snow-course when I was there on February 28.

"I feel from your letter that you may not yet quite fully comprehend the snow conditions at the Mary's River - 76 Creek divide. They are rather difficult to explain but I enclose a sketch (Fig. 4) so that you may have at least a diagrammatic picture. Because the morning was quite dark and stormy I did not take my camera the day we measured the snow. However, you can see from Figure 4 that there is only one route to take between the divide and the snow-course. This route is through a 40-foot break in the cornice and onto the soft snow under the cornice-rim. We realize that the cornice itself might not be such a dangerous hazard, but consider that the looser variable snow below the cornice is.

"Although we took a route from the divide down into the basin as vertically as possible (broken line on Figure 4), if the snow had been of different consistency it would have been possible to get back up only by crisscrossing more horizontally on the soft fresh snow. It seems that the climbing out of the basin, up the steep slope (50 to 60 per cent) below the cornice-rims might cause the most disturbance. Throughout the trip there are all variations of snow, from the soft fresh snow to the layers of crust. On some side hills the crust is so hard and the slope so steep that only the metal edges on the skis make it possible to cross.

"Going to the West Mary's River course from Pole Creek is practically out of the question. There are more steep slopes and high ridges to cross than the present route from Jarbidge. Even if such a trip were feasible at least six days would be required to the course and back to Pole Creek."

Since the percentage relationships of the snow-cover are nearly uniform over wide areas, it has been suggested that an alternate snow-course be laid out at the foot of the final ascent into Marys River Basin, whose record can be used whenever the traverse over the cirque is dangerous.

This course requires a series of three shelter-cabins but other essential snow-surveys can be made en route. A helicopter plane would solve the problem both of time and of peril. For the even more isolated areas in Oregon, where public service employees cannot be absent long, R. A. WORK in charge of the Oregon Cooperative Snow-Surveys has suggested airplane-transportation.

The Tetons--The close association of avalanches, scenic beauty, and research in the National Parks is revealed in the following letter by FRED J. BROWN, Guide in Grand Teton: "We have been having some splendid tours from the new Park cabin at the forks of Cascade Canyon (the deep canyon which feeds Jenny Lake). Unfortunately we missed a splendid opportunity to make a complete movie of a fine, wet-snow avalanche. No one in the party had a movie camera at the time. The slide ran for perhaps ten minutes in successive falls off the south exposed St. Johns summit ridge, and stopped within a hundred yards or so of our safe position. How I love to hear them thunder!

Fig. 3--Highway 40, Donner Summit (restricted military area
(Nevada Photo Service)

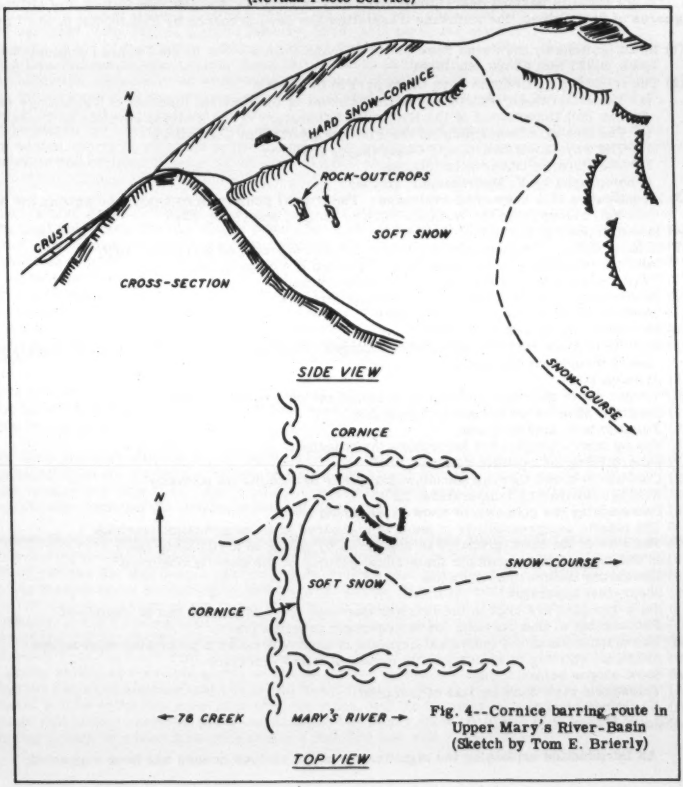


Fig. 4--Cornice barring route in
Upper Mary's River-Basin
(Sketch by Tom E. Brierly)

"By the way, what's the dope on the melting of ice and névé, including surface-harsch by Sun? Why does the surface (including of course snow as well) melt in 'leaves,' laminae, and tiny pinnacles? I have found that our best corn-snow (there seems to be little generic similarity at least in formation among the types called 'corn') is formed by the deep irregular melting of névé-harsch. The surface becomes deeply serrated while the heat at the same time destroys the crystalline structure formed by the previous night's freeze. These serrations are composed, so far as I can see, of a sort of rotten ice, like any clear ice which has been long in the direct Sun. They then collapse into the characteristic coarse crystals called 'corn-snow.' Rather fragments of decomposed masses than crystals formed by positive sublimation. You should see, by the way, the remarkably varying blues and greens of our frozen waterfalls in the canyon walls."

Swiss-avalanche film--The Swiss-avalanche film referred to in the Report of 1941 was forwarded by the Swiss Government in its diplomatic pounch to Washington and was then sent on by Secretary FLEMING via air-express in time for showing at the Regional Meeting of the Snow-Survey Conference at Pasadena. The United States Government waived customs dues because of the generous act of the Swiss Government in providing the film at bare cost.

Since the film carries descriptive titles only in German, French, and Italian, the official languages of Switzerland, the following translation has been prepared by FRANÇOIS E. MATTHES:

(1) Investigations by the Swiss Snow and Avalanche Commission in the Parsenn Region: Weissfluhjoch, 8,727 feet above sea-level
(2) The following institutions have taken part in this work:
  (a) The Mineralogic-Petrographic Department of the Federal Institute of Technology (Zurich)
  (b) The Soil Department of the Hydraulic Laboratory of the Federal Institute of Technology
  (c) The Geologic Department of the Federal Institute of Technology
  (d) The Physico-Meteorologic Observatory at Davos
  (e) The Parsenn Observation Station
  (Photographs by E. Meerkämper, Davos)
(3) Investigation of a snow-slab avalanche: The frontal Schwarzhörn avalanche across the downhill ski-course from the Weissfluhjoch to Küblis, March 30, 1937
(4) Investigations at the line of fracture
(5) Gliding sheet = disintegrated surface of ice-crust produced November 1936
(6) Internal resistance of the snow-layer (diagram of compaction)
(7) Taking snow-samples for laboratory investigation
(8) Determining plastic stretching and tensile strength
(9) Work in the field and in the laboratory
(10) Measuring the pressure of snow
(11) On a level snow-field the successive changes in each individual snow-layer are closely followed throughout the winter
(12) Anemometer
(13) Trench cut in the snow in order to examine the successive layers
(14) Diagram showing progressive compaction
(15) Temperature-measurement
(16) Taking snow-samples for laboratory investigation
(17) Determining the specific gravity
(18) Cold air is blown through the snow-sample to determine its porosity
(19) Average laboratory temperature, 23°F
(20) Determining the cohesion of snow by shearing tests
(21) The plastic compressibility of snow is measured in a compression-machine
(22) The size of the snow-granules is measured by means of a vibrating sieve
(23) In the compression-machine the gradual settling of the snow is observed
(24) Measuring the creep of the snow
(25) Shear-test apparatus
(26) Snow-samples are kept in the refrigerator until their structure can be examined
(27) Preparation of thin sections for microscopic examination
(28) The orientation of the individual crystals is observed under a polarizing microscope
(29) Artificial starting of avalanches by means of trench-mortars
(30) Snow-slopes before firing
(31) Telescopic view showing line of fracture
(32) A particularly effective hit
(33) Snow-slopes after firing

An introduction explaining the significance of the various scenes has been suggested.

Organizations of all types have shown the film, and more are waiting when autumn quickens interest in winter activities. The Army has reproduced the film and may add a sound-track. The Forest Service is making a copy with explanatory titles in English. The International Commission of Snow and Glaciers that is circulating the film also is planning to obtain a positive in English in order to preserve the tri-lingual film for use abroad after the war is over.

The film is available to all. Only the cost of insurance and transport is requested, but most of the organizations have generously sent in a small voluntary gift to complete payment on the original cost of the film and build up a fund for a duplicate in English.

The Swiss Glacier Commission provided a negative of the film for purposes of reproduction and has generously granted free use of the illustrations in its handbook "Lawinen" [summarized in Trans. 1941, p. 978] and will provide negatives of the illustrations at cost.

Sport

The preceding section on safety is merely the background and mood of sport and transport which form the other half of public interest in snow. So universal have snow-sports become that the United States Travel Bureau features winter ski-fields with scenes of natural beauty. The following excerpts from Travel West of January, 1942, will serve for others:

"Ski-time on top of the Nation--Skiing on top of the Nation is in full swing, reports the Colorado State Department of Information. Snow fell as early as the middle of November and since that time highways, especially on week-ends, have been crowded with ski-bearing automobiles traveling to Colorado's 33 ski-courses, which are located for the most part in the front yard of the greater portion of its populated centers.

"According to the United States Forest Service, an increase of ten per cent in those participating in winter sports is expected in their ten developed ski-areas and the more or less undeveloped slopes within national forests. Last year 110,000 skiers used Colorado Forest Service areas."

"Mount Baker National Forest Winter Sports--An article in the December issue of the Great Northern Goat points out the advantages possessed by Mount Baker, near Bellingham, Washington, as a winter-sports area. Powder-snow is to skiing what low-scudding clouds and brisk winds are to duck-hunting or a dry field and clear weather to football. And, because it offers many days of powder-snow conditions, Mount Baker is rapidly becoming one of the most popular ski-areas in the northern Cascades. The deep snows are reached throughout the winter season via a double-lane state highway to the door of Mount Baker Lodge. From Bellingham, served by the Great Northern's Seattle-Vancouver line, it is only a short drive. The 'Empire Builder' from Chicago and the Twin Cities makes direct connections in Seattle with the morning train to Bellingham and Vancouver."

The Mount Baker Area in forestation, mountain slopes, and avalanche-perils offers ski-troops the same facilities for snow-training as Mount Rainier which is in the National Parks where restrictions on use prevail.

Deep snow and high altitude extend skiing well into summer. Year-round skiing must depend upon the mobility of the public and skiers to travel southward with the summer even to Chile. There ski-slopes are said to be superb but lie frequently above available ski-lifts, thus necessitating an all-day climb for an evening's descent.

"Lassen Ski-tournament [News Bull., U. S. Travel Bureau, June 1941]--The top-ranking skiers who are entering the Mt. Lassen Mid-summer Ski-tournament, to be held in Lassen Volcanic National Park on June 29, will have to use brains as well as skill and speed in running the featured Inferno and Slalom races according to JOHN C. PRESTON, Park Superintendent.

"Two of America's leading course-setters will place the flags in these events. Dr. JOEL HILDEBRAND of the University of California will set the Slalom courses and Dr. FRANK HOWARD, Manager of the California Ski-team, will set the Inferno courses. The rugged terrain on the slopes of the Lassen Peak together with the course-setting skill of these two men will present a real test of skiing ability and provide plenty of thrills for the spectators.

"Entries received indicate that one of the finest fields of skiers ever to enter a California tournament will be on hand for the mid-summer meet, and the exceptionally heavy snowfall of last winter will insure excellent snow-conditions. The heavy snow-pack will also permit the construction of a jump on which distances of more than 200 feet will be possible."

As attractive, however, as the ski-tournament at the top of Mount Lassen are the spring flowers retarded by the deep snows into autumn.

"Spring flowers now blooming in Lassen Park [News-item, September 1, 1941]--Spring has just arrived in Lassen Volcanic National Park, according to Ranger-Naturalist GEORGE O. HALE. Wild flowers that in other areas have already bloomed and died are just coming out at Summit Lake, Kings Creek meadows, and along the Bumpas Hell Trail. Heavy snowfall last winter retarded the growth of vegetation in the high country and the 'spring' wild-flower display will be at its best during the first two weeks in September, HALE added."

National defense--The needs of national defense have directed rather than restricted winter sports. Quoting again from Travel West of January, 1942: "Sun Valley for relaxation--Sun Valley, Idaho, has curtailed none of its entertainment, according to a Union Pacific release, but is building its entire program around the realization that outdoor sports and indoor recreations alike provide guests with temporary respite from the worries caused by the emergency. Sun Valley's winter recreational facilities have been geared to meet this need and the reservation-list is reported to be the heaviest in history."

"Highway 40 (Donner Summit)--According to information released by the California State Chamber of Commerce, military officials are desirous that winter sports be carried on as usual. For National Defense reasons, however, the use of such areas as border the railroad right of way in the Highway 40 Area have been restricted as to use. Skiers are urged not to approach within 200 yards of the tracks on either side. Special care should be used in parking cars so as to leave at least a 20-foot strip down the center of the road to permit uninterrupted flow of traffic at all times. As far as possible, warnings will be posted at closed areas to mark them plainly for skiers. Details concerning restrictions include the following:

"At Auburn Ski Club, passing over the tunnels or approaching the tracks is not allowed; at Soda Springs, the area from Soda Springs to the Summit Lookout Station and Maintenance Station between the highway and snow-sheds cannot be used, with all areas north of the highway open except for a small area at the Summit, and a 50-yard passageway across the tracks at Soda Springs will give access to the Beacon Hill Area and the Sugar Bowl; no 'Snowball Specials' will be operated until further notice and regular trains will carry winter-sports fans; Norden Ski Hut and Station will be closed to public use; passengers will detrain and entrain at Soda Springs to use the facilities of the Norden Ski Club, Vanderfords, and the private clubs at Norden and the Sugar Bowl."

"To keep production and morale at highest levels the Nation must maintain travel- and vacation-facilities, or the human machines upon whom Democracy depends will not be kept at their most efficient pitch."

Transport

Sport naturally fades into transport and is a part of it. Furthermore military and civilian aspects of it are similar except that the former requires priority though the needs of both are identical.

Motor-sleds--Through impetus given by the Army, winter transport has now become an insistent problem centered on overcoming deep unconsolidated snow. Several types of motor-sleds from air-propeller through spiral-drive to caterpillar-tread have been successful on crusted or compacted snow, and each has special advantages. The caterpillar, however, under recent tests approaches the ideal requirements of maximum buoyancy and traction with minimum friction where propulsion must be provided by the snow itself. No sled, however, can surmount all snow-obstacles at all times.

For heavy traffic where the snow is relatively shallow is the sled-train drawn by a caterpillar-tractor. Such trains bear heavy freight to the camps and mines of lower Canada, but are confined to definite routes along roads and frozen water-courses. While the snow offers little obstruction, the river-ice sometimes breaks under the weight. Airplanes flying the route keep sharp lookout and are readily summoned.

This type of traffic has now been extended to Alaska. Here a tractor-train of three sleds rushing heavy equipment for air-bases broke through the ice near the center of a lake. "Tripod-derricks were rigged up for recovering the train, and a diver then attached cable-slings to the rigs. The crews worked six days in salvaging the freight, sleds, and tractor. The tractor was pulled up a ramp carried on long timbers to distribute the load. Cleaned, drained and fitted with new gaskets, the machine was ready for use within a few days" [Eng. News-Rec., May 14, 1942].

Fig. 5--Tucker "Sno-Cat" in action (courtesy E. M. Tucker; for its amphibian ancestor see Trans. 1941, p. 971)

The "Sno-Motor" described in the last Report of the Committee on Snow [Trans. 1942, Part I, pp. 161-163] is a heavy-duty caterpillar of a single drum to maintain buoyancy on deep snow, and is steered by the tow-lines attached to a pontoon-sled. It was selected by the Southern California Edison Company for winter emergency-service particularly for the families of employees at Florence Lake in the heart of the High Sierra. Here the Lofbergs, while operators for the Company, became John Muirs of wild life portrayed in Sierra Outpost.

Of the lighter sleds that depend upon the snow-surface for traction, the Tucker "Sno-Cat" (Fig. 5) appears most adjustable to various conditions but requires several improvements. Snow-friction is eliminated except on the steering-ski and the body is set high to permit the two driving-belts to compress the snow to stability. Still greater height of bed is desirable where snow is unusually deep and unconsolidated. Larger lugs are necessary to maintain traction both in dry new snow and on wet soft snow overlying crusts. The ski and belts should be oval to overreach the snow. The latter should be equipped with a brake for each to prevent spinning in snow of uneven density.

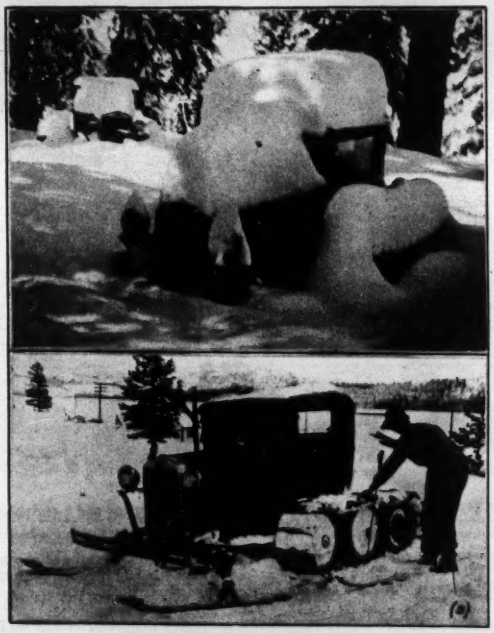


Fig. 6--Converted Ford coupe, Ice Lakes Inn
(A) In new snow; (B) on old snow
(Courtesy Ice Lakes Inn)

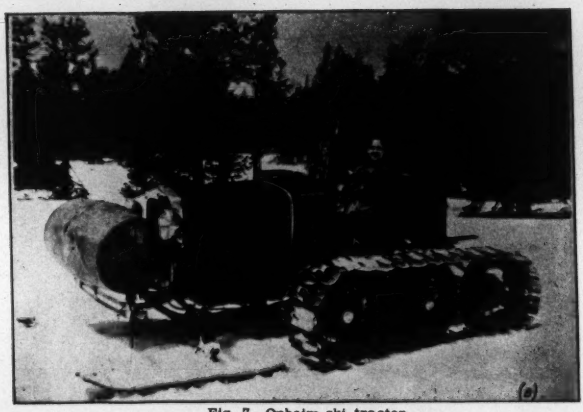


Fig. 7--Opheim ski-tractor
(A) Plan and elevation; (B) on old snow

If the motor fails, the belts can readily be removed, thus converting the caterpillar into an ordinary sled for emergency-towing. Under favorable conditions, the "Sno-Cat" is capable of attaining a speed of fully 20 miles an hour and can climb slopes negotiated by the land caterpillar in summer.

Its capacity can readily be expanded by a larger platform or trailer and a cellophane cabin can easily be provided. It can draw a train of sleds.

Of similar character is a converted Ford coupe, seen at Donner Summit and shown in its essential details in Figure 6. It climbed mountain grades so readily and lurched down them so safely that the name "Lilting Lizzie" became its immediate designation.

As a means of conserving time and energy on cross-country ski-runs, ALVIN W. OPHEIM has invented a tiny caterpillar-tractor (see Fig. 7) to act as tow-car for the skier who steers the

Fig. 8--Snow-plane in Jackson's Hole (Photograph by G. H. Simmonds, U. S. Bureau of Reclamation)

tractor and regulates its speed by remote flexible-cord control. Toboggan or sled as well as skier can be towed. Its value will be greatest on uphill or level slopes; it may prove too slow on down-hill runs.

In contrast to the caterpillar-sleds that obtain traction from the snow, the "Sno-Plane" seeks its traction from the air and uses the snow merely for buoyancy.

The "Sno-Plane" shown in Figure 8, built by Price and Davis of Durango, strangely was developed in the wild country of southwestern Colorado and has been successfully used by the United

States Reclamation Service in the Jackson Lake Region adjoining Yellowstone National Park. The small shelter-cabin rides low on three duralumin-skis, one foot wide and seven feet long, the one in front functioning also for steering. To avoid injury to the propeller open trails must be used. On smooth packed snow, as on Jackson Lake, a high speed is possible. On sticky snow little resistance is noted because of the constant thrust of the propeller. The 150-mile snow-survey route that once required ten days for skiers can now be accomplished in two and can be made between storms rather than through them.

To speed their mechanical development, research should be conducted on the relation of snow-friction and cohesion to the movement of sleds. This task might well be assumed by the National Bureau of Standards or Forest Service or Army, the two latter having an intimate interest in travel over snow. The National Research Council also seems to be investigating the problem of snow-transportation. The Canadian Research Council has done similar work in reducing snow-friction on aeroplane-ski and has issued a final report [G. J. KLEIN, Snow characteristics of aircraft skis, Report MM-57, Nation. Res. Coun. Canada, Div. Mech. Eng.].

If initial cost is not too great the helicopter (called autogiro) was suggested by H. P. BOARDMAN in a previous Report as a substitute for sleds where even small openings are available for landing. It may become the snow-surveyor's friend.

Sectional ski--As an adjunct to preliminary travel by auto or airplane a sectional ski has been designed by J. J. McLAUGHLIN, Sierra Club, Norden, California, that can be stowed in small compass or strapped to the pack where hiking over bare ground alternates with skiing. They are particularly adapted for ski-parachutists who should descend with their ski close at hand and ready for immediate use. Indeed in soft deep snow it would be as difficult to recover ski dropped by a separate parachute as for a swimmer to regain his life-preserver.

Shelters--Dependent upon the weather, shelter on snow-trips may vary from a sleeping-bag on the open snow to a pit in the snow, a snow-cavern, a tent, an igloo, or a permanent cabin fully equipped and easily entered whatever the depth of the snow. Details are given in Brower's "Manual of ski-mountaineering" and the Chairman's fifty-years story of "Snow sport and transport" [Sci. Mon., March, 1942] in his series on the "Human side of snow."

Shelter-huts with "Santa Claus chimneys" have become standard where the snow is exceptionally deep. The design by the Nevada Cooperative Snow Surveys (see Fig. 9) is the original but the two views in Figure 10 (A and B) by the Division of Irrigation of the United States Soil Conservation Service represent later designs for extreme snow-depths in the Cascade Mountains of Oregon.

Two new cabins have been constructed in the Toiyabe National Forest, Nevada, by the United States Forest Service as shelters for snow-surveyors, one of these in the headwaters of the Reese River where snow-surveying now for the first time has been established.

Shelter-cabins for air-pilots--The fortunate discovery of a cabin last winter by an airplane-pilot grounded in the wilder part of the central Sierra Nevada caused W. W. McLAUGHLIN, Chief of the Division of Irrigation, to request all owners of cabins to post maps in them showing routes and distances to nearest accessible habitations. Maps of the shelter-cabins along airplane-routes will be placed on board for the pilots.

The Associated Press in the following news-item of December 1, 1941, from Washington, D. C., has helped to launch the plan: "As a safety-measure, army and commercial air-line pilots flying over mountainous and isolated regions of the West are to be supplied with maps showing locations of shelter-cabins maintained by State and Federal snow-survey agencies.

"These cabins are located far from any other shelter. Officials believe they might be the means of saving the lives of persons forced down in the heavy snows of the Sierra and Rocky Mountains.

"The shelters are stocked with sufficient food to supply one man for six weeks, and with fuel and emergency first-aid kits. They also are supplied with skis and snow-shoes and directions to the nearest ranch or village.

"Some of the cabins are visited monthly by snow-surveys, and all are visited at least once in the fall and twice during the winter months. Snow-surveys are made for use in forecasting the amount of water that will be available for irrigation, power, and domestic use during the coming summer."

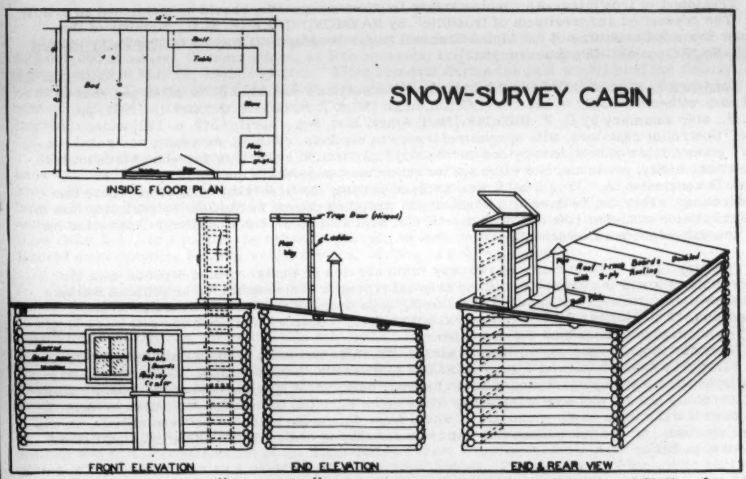


Fig. 9--Original design, "Santa Claus" cabin, by Nevada Agricultural Experiment Station, for Center Mountain, Sierra Nevada

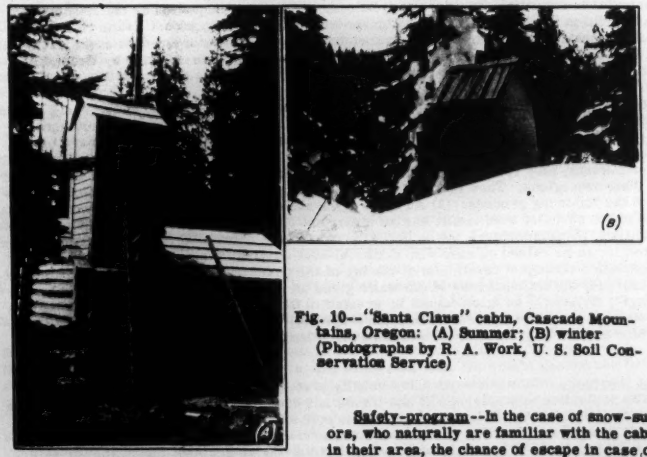


Fig. 10--"Santa Claus" cabin, Cascade Mountains, Oregon: (A) Summer; (B) winter (Photographs by R. A. Work, U. S. Soil Conservation Service)

Safety-program--In the case of snow-surveyors, who naturally are familiar with the cabins in their area, the chance of escape in case of accident has been improved by a new rule of the Forest Service requiring additional members in the snow-survey crew. L. E. McKENZIE, District Forest Ranger for the Ruby Range, Humboldt National Forest, Nevada, wrote at the beginning of the past snow-survey season: "The safety program for the Humboldt National Forest for 1942 provides two men on one-day trips and three men on overnight trips. This will require sending three men on the Lamoille Canyon Survey." This Forest suffered two serious accidents the previous year from avalanche and ski, the former being fatal to one of the members of the party.

Treatment of frostbites--As supplementary to other safeguards, should be mentioned an article on "The prevention and treatment of frostbite" by RAYMOND GREENE, M.D., Member of the Mount Everest Committee of the Alpine Club and Royal Geographical Society in The Polar Record [v. 3, No. 23, pp. 481-488, January, 1942].

Exposure to wind--It has been the Chairman's experience that wind of 70 miles per hour at 0°F may wither the flesh. C. E. CORLETTE, M.D. [Med. J. Australia, October 18, 1941, pp. 441 ff.; also summary by C. F. BROOKS, [Bull. Amer. Met. Soc., April, 1942, p. 182] under the title "Control of heat-loss, with special reference to blankets, clothing, exposure, and resuscitation" gives a table of heat-loss by convection and vaporization at various degrees of temperature, relative humidity, pressure, and wind; but the minimum temperature quoted is only 38°F. The author's conclusion is: "For a cold, wet, shocked person, the first thing to do is to reduce the wind-cooling. This can be done by a wind-break, wrapping patient in blankets or enclosing him in a resuscitation-chamber (the last only if artificial heat available), but a physician must stand by lest the patient die from overheating!"

Two-way radio--The question of two-way radio service at shelter-cabins depends upon the opportunity to warm the batteries to their original strength. This should not be difficult where fire is available and there is time. The following experience of the British Canadian Arctic Expedition, 1936-40, corresponds in general with battery-recovery in connection with recording precipitation-gages, discussed under equipment:

"In order to get a time-signal in mid-winter, the radio had to be brought into the snow-house and warmed up from about -40°F to at least 0°F to make the batteries work. In practice it was usually found more convenient, and the results were better, if it was warmed above +32°F. However carefully the set was kept wrapped up while being warmed, some hoar-frost always formed; and, even if warmed in an air-tight box, it would frost during the night, or between signals, unless it was put away, or the snowhouse was kept warmer than is ordinarily possible" [Polar Record as above, p. 493].

Igloos in the Alps--Also in the issue of Polar Record of January, 1942 [pp. 512-517] appear specifications for igloos and mention of plywood-huts for use where snow is cohesive or light building-material is essential. In Greenland, balsam-wool was transported by the Michigan Greenland Expedition far inland by boat and on the back of packers up Mount Evans (elevation 1,200 feet above sea-level) as a lining for its meteorological observatory, whose outer walls were of tundra. Plywood-huts, already used in the Antarctic, have now been selected by Hudson Bay Company in place of frame-dwellings.

Although the igloos have long been considered a polar specialty, LOUIS MALAVIELLE and his wife have experimented with the building of igloos in the Alps "until they have not only become expert but regard the technique as essential for mountaineers as well as for polar travellers." That they have put their theories to a most exhaustive test will be evident from the fact that, without guides or porters, they spent 20 days above 3,200 meters in July and August without any shelter beyond their own igloos. They recommend the use of igloos in preference to tents for mountain-work on the following grounds: (1) An igloo gives absolute security even in the worst blizzards, and absence of the sound of wind inside has an important psychological effect; (2) whatever the outside temperature, the temperature inside the igloo never falls below 0°C (the temperature of melting-snow) and it can be raised quickly with artificial heat up to 20°C or even more; (3) there is adequate ventilation through a small hole at the top of the dome and by the entry of air at the bottom of the door; (4) the transparency of the walls gives an agreeable diffused light either by day or in moonlight; (5) even if an igloo cannot be erected in the very worst storm, it can be built in weather in which it would be impossible to pitch a tent; (6) the weight of materials needed for building is only about 700 grammes (1.5 pounds), much less than that of the smallest mountain tent.

Accident insurance--Snow-surveyors are usually protected by State or Federal insurance systems. The protection of employees at ski-fields, however, has sometimes proved inadequate and the individual skier, like the traveler, unless he possesses standard accident insurance, is wholly without protection. For this reason the Commercial Casualty Insurance Company of Newark, New Jersey, has "originated and provided exclusively an accident insurance for skiers. Fifty cents premium per day will provide indemnity for ski-injuries up to $1,000 for accidental death." It is hoped, however, that the assurance "You can enjoy skiing without the unknown fear!" may not relax the skier's sense of responsibility for himself and others.

Snow-removal

Snow-removal is now practiced in 36 snow-belt States and Canada, at a cost exceeding $20,000,000 annually. In some states, as Pennsylvania, the budget is in the millions. Engineering News-Record of May 28, 1942, reports: "Snow-removal during the past winter cost the Pennsylvania Highway Department $3,603,797.71, a drop of more than $1,000,000 under the cost of the winter of 1940-41. The program covered 19,921 miles of State-controlled highways and secondary roads."

Snow-rolling--Alleghany County (Pittsburgh, Pennsylvania) air-port has supplemented its snow-burner [Trans. 1941, pp. 968-969] by a snow-roller to create a smooth firm surface on which planes may land and take off [Eng. News-Rec., February 5, 1942]. It resembles the old land-roller except that it is eight feet in diameter, ten feet long and weighs 1,000 pounds, and the ends are closed to prevent snow accumulating inside. At one pass it has reduced the depth of snow from 6-1/2 to 2 inches and smooths out ruts as they occur. It is valuable to fields with limited snow-handling budgets where removal of snow is not contemplated.

Calcium chloride--The harmful features of calcium chloride on highways are mentioned in the report from New England by Dr. HENRY I. BALDWIN: "State Highway Departments are resorting to use of more calcium chloride than ever. Formerly a Vermont car could be told by the porous condition of its fenders, caused by this substance. Instead of being mixed with sand, calcium chloride is now often spread on the roads 'straight' through rotary spreading-devices. This results in a more or less permanently slushy surface until the road is completely bare. High calcium-chloride content of the soil along roadsides has resulted in injury and death of shade-trees in some instances, especially in the vicinity of highway sand-dumps."

Snow-drift control--More extensive planting of trees and shrubs is proposed by CARLOS G. BATES and J. H. STOECKELER of the Lake States Forest Experiment Station for prairies and plains of Northern States as a substitute for slat snow-fences. Their report, "Planting to control drifts on highways" [Eng. News-Rec., July 16, 1942, pp. 70-74], covers snow-profiles formed by plantings, best species for snow-fence, care of live snow-fences, and costs of planting snow-fence.

Unlike the Danish "live fences," grown on embankments to deflect the strong sea-wind, those of the northern prairies and plains will serve both as shelter-belt and snow-fence. "Since the present system of using slat-wire snow-fences costs about 25 cents per 100 feet per year, it is probable that the simplest type of plantings, consisting of one or two shrub-rows, might cost no more over a period of years." Such hedges will greatly relieve the bareness of the highways and with some planning can even be used to beautify the landscape.

Instrumental equipment

Interest is still being centered on the further improvement of precipitation-gages and snow-samplers.

Recording-gages--Since recording-gages, the present center of interest, have a long tradition which should be preserved, the following from the inventor of the Fergusson self-recording rain- and snow-gage (patented 1889) will be highly prized (see Fig. 11):

"The weighing-gage goes back many years; there may have been one in use in England before 1870, but I am not sure of this. DRAPER'S recording-gage (about 1875) measured snow and rain, the receiver being provided with a lamp for melting snow as it fell. ROTCH'S gage was described by him in the first volume of the Blue Hill Observations (1887):

> 'The self-recording rain- and snow-gage constructed after the writer's design, by RICHARD BROTHERS of Paris, has been in use since March, 1886. The receiver in this gage rests upon a platform-balance, and when rain falls its weight causes the balance to record the amount and time of occurrence upon a revolving drum, as in the other RICHARD instruments. Tracings of this gage, slightly reduced in size, are shown. To adapt it to snow another receiver is used, which is deeper, with an inner shield to prevent clogging by sleet. The author believes this to be the first successful attempt to record snow automatically without first melting it. The records of the registering-gage agree fairly well with those of the standard with which they are compared.'

"My recording-gage was suggested by the ROTCH gage, the measuring device being a spring-balance instead of the platform-scale which had given more or less trouble. The first instrument was built during the summer of 1888 and described before the New England Meteorological Society, at its annual meeting, October 16, 1888 [for brief description see Amer. Met. J., November, 1888]. Inquiries for the instrument having come in, Mr. ROTCH suggested that the Draper Com-

Fig. 11.--Fergusson weighing and recording rain-and-snow gage

pany manufacture it; but failing to effect a satisfactory arrangement, I employed a Boston instrument-maker to supply the few that were needed, at actual cost. This arrangement continued until 1895, when HENRY J. GREEN, maker of precision barometers and thermometers, became sole agent for several years. In 1904, the International Equipment Company of Boston undertook the production of the instrument, which, about 1918 was redesigned to adapt it to use in connection with rain-insurance, and its manufacture was assumed by JULIEN P. FRIEZ of Baltimore. Since that time the demand for this gage has increased very rapidly and modifications to meet particular needs have been produced. I understand that, at present, there may be more than 1,000 in use, chiefly in the West. The above is somewhat detailed but it seemed advisable to get a short history on record, partly for file at Blue Hill. Not many instruments survive as long as 54 years. The first descriptive circular of the gage was printed in January, 1890."

The Fergusson gage has become the standard instrument in field-studies of the effect of varying intensities of rain. It is also "definitely superior" reports Dr. CHARLES F. BROOKS [Bull. Amer. Met. Soc., April, 1942, p. 178], "in snowy as well as rainy weather than the HELLMANN-FUESS gage of Germany, which cannot measure the water-content of snow directly and will not function in below-freezing weather."

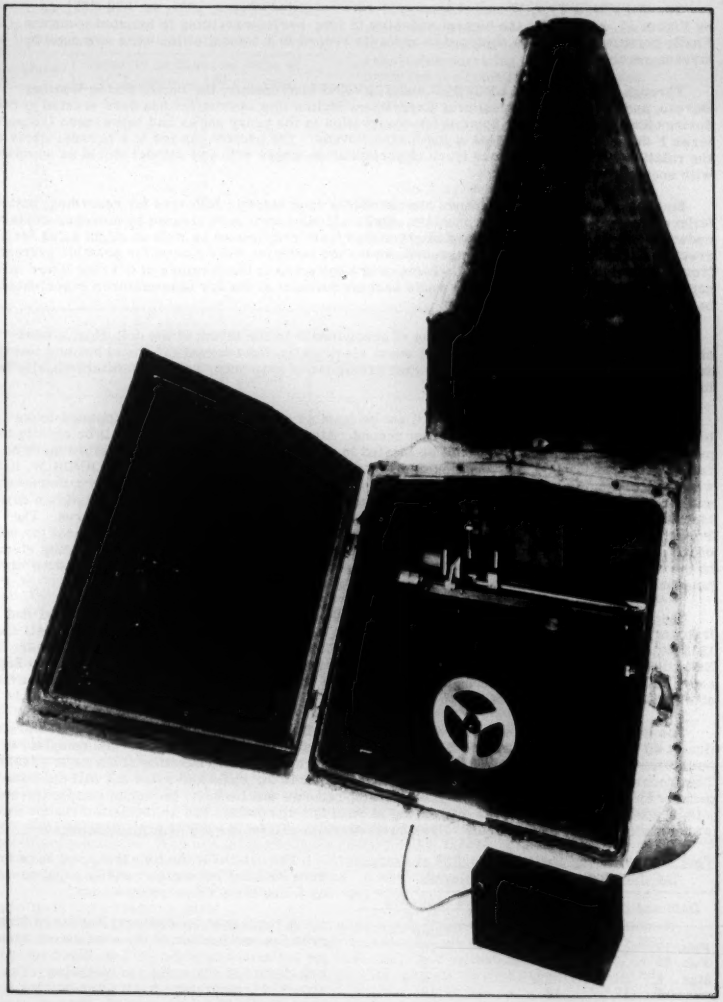


Fig. 12--Stevens annual snow-and-rain recorder, manufactured by Leupold and Stevens

The STEVEN'S Type-W annual snow-and-rain recorder [Trans. 1934, pp. 632-633], as shown by Figure 12, represents the highest endeavor in long-period recording in isolated locations. If finally perfected, it will be equipped to radio its record to a central office as is now done by stream-recorders.

Through cooperation of LEUPOLD and STEVENS Instruments, the United States Weather Bureau, and the Nevada Agricultural Experiment Station this instrument has been erected at Soda Springs Station near Donner Summit for observation in the heavy snows and below-zero temperatures F that prevail at the crest of the Sierra Nevada. The project has led to a broader study of the relative accuracy of various types of precipitation-gages with and without shield as compared with snow-surveying.

Since the STEVENS gage depends almost wholly upon electric batteries for recording, battery-failure has constituted the chief problem. Short-circuits have been created by mercury-contacts under delicate adjustment to record slight losses from evaporation as well as slight gains from precipitation. Rising water in the ground, where the batteries were placed for possible protection from frost, also drowned them out. Tests of dry batteries at temperature of 0°F and lower indicated that in any case the batteries would become dormant at the low temperatures experienced in the mountains.

To prevent accumulation or freezing of precipitation in the throat of the collector, a wind-charger was installed to keep the metal warm electrically, but the charger would become inactive during periods of light winds or calm, when precipitation may occur and temperature usually is lowest.

Use of a weight-driven recorder will not be feasible since the ultimate development looks toward radio transmission of the current record. Attachment to a power-line will be equally impossible since the instrument should be located in remote places. Recourse therefore must be had to wet batteries that may function despite cold, if they have sufficient life. VERNON W. RUPP, who is directing the test, has suggested "Flamo or similar gas controlled dually by a thermostat and a control operated during open periods of precipitation, using a very small pilot-flame during high temperatures but increasing when precipitation occurs with freezing-temperatures. The Forest Service is using, successfully, a thermostatically controlled gas-heating element for some of its recording tipping-bucket gages. Our observations indicate that the idea of a heating element in the catch-ring is very desirable for use on gages wherever freezing-temperatures occur simultaneously with precipitation, even on the smaller gages."

Susceptibility of batteries to cold--Failure of the dry-batteries at Soda Springs Station and freezing and bursting of similar batteries at Mount Rose Observatory (elevation 10,800 feet) about 1910 at prolonged minimum temperatures of -10°F caused the testing of a set of Ever Ready Batteries No. 718 with the aid of the Chism Ice Cream Company and ERNEST MACK, Radio Engineer, both of Reno. Temperatures of 0°F and -25°F were employed with opportunity to recover at warm room-temperature of 65° to 70°F.

The lower temperature was more extreme in its effects but both temperatures stopped practically all chemical interaction of the battery-elements. Recovery was 80 per cent complete in both batteries within 24 hours after transfer to the warm room. No bursting of the cells occurred. This recovery-ability may make the batteries serviceable for radio and autos but will not compensate for prolonged periods when precipitation-records will be lost. Minimum temperature of -16°F occurred frequently even into spring at Soda Springs Station and no insulation except earth-warmth will protect the batteries. Even earth-warmth will be low for best functioning.

Test of Ever Ready Batteries No. 718 at Chism Ice Cream Company, Reno, Nevada

Date and time		Temperature of exposure	
		Approx. 0°F	-25°F
	h	amp	amp
Feb. 17	...	12.5[a]	18[a]
Feb. 25	...	8	2
Mar. 6[b]	...	0.5	0
" 7,	17	10	15
" 9,	17	10	16
" 14,	12	7	14
" 16,	12	8	15
Apr. 9,	17	9	16

[a] At 6 volts. [b] Transferred p.m. March 6 to warm room at 65°-70°F.

The details of the test are given here for their interest but can be readily supplemented by fuller tests reported by others.

A request to the National Bureau of Standards for verification of the experiment brought its Letter Circular No. 677 on Electrical characteristics of dry-cells and batteries. The standard temperature for its dry-battery tests is 21°C (70°F) but because of "the increased interest in the performance of all kinds of batteries at low temperatures," the following results (see next page) were supplied.

Effect of temperature on the capacity of dry-cells (Tests on a 22.5-volt unit of F-cells discharging through 1,250 ohms to a cut-off voltage of 15 volts)

Temperature		Capacity as based on value at 70°F taken as 100 per cent
°C	°F	pct
38	100	140
27	80	115
21	70	100
16	60	90
4	40	69
- 7	20	48
-18	0	27
-29	-20	6

The report concludes: "Dry-cells which have been frozen are usable after they have been thawed and brought to a reasonable operating temperature. When batteries are taken from cold-storage, moisture is likely to condense on them ('sweating'). This should be avoided as far as possible since the jackets may be destroyed and electrical leakage increased."

The Burgess Battery Company has furnished the discharge-curves, as in Figure 13, of "10-A" cells (National Bureau of Standards "F"-cell) at various temperatures (discharged on 83.5 ohms per cell continuous).

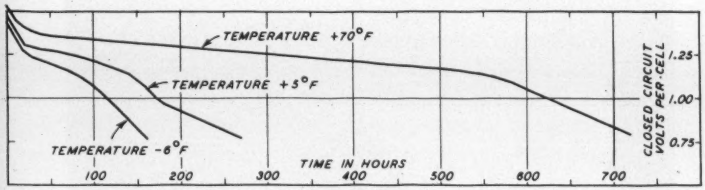


Fig. 13--Burgess Battery Company's discharge-curves for cells of type 10-A at various temperatures

The extremes of relative efficiency at 70°F, + 5°F, and - 6°F are 710, 270, and 160 hours respectively, or rating 70°F as 100 per cent, the efficiency at + 5°F and - 6°F falls to 38 and 22.5 per cent. Other details are provided in "Characteristics of the size-F dry-cell" by H. E. LAWSON and F. J. KIRKMAN [Trans. Electrochem. Soc., v. 70, pp. 441-455, 1936].

Storage-batteries--Inquiry inaugurated regarding the endurance of storage-batteries has brought the following comments from Dean STANLEY G. PALMER, College of Engineering of the University of Nevada, and generous offer to make the problem a formal project.

"You have requested information concerning the possibility that the use of some type of storage-battery might give better results in the operation of your weather-recording equipment at Donner Summit than the dry-cell type of primary battery which you have been using.

"I would be glad to undertake a series of experiments with the view to determining the operating characteristics over a considerable period of time and at the low temperatures which you have during the winter at the crest of the Sierra Nevada.

"I believe it quite possible that the lead-acid type of storage-battery in common use on automobiles today might, if we use sufficient capacity in ampere-hour rating, supply the required current over the period of months which you have stated would be required, without having the specific gravity of electrolyte drop to a point where the battery might freeze. I believe that there is also a possibility that the Edison alkaline type of storage-battery, containing potassium-hydroxide solution, might meet the requirements of this service. It would be necessary to make these tests over a period of time as long as six months, I would say, after batteries and equipment were secured and tests were ready to start.

"We might also carry on some tests on dry-batteries if you thought that further information on the operation of such batteries is desirable. My only comment on the use of dry-batteries is that you might overcome the complete failure which you have described by installing batteries of very much larger capacity. This would make the discharge-rate per cell very much lower and the batteries would naturally last longer."

Comparison of types of gages and snow-surveying--A STEVENS 30-day recorder with tower has now been provided by LEUPOLD and STEVENS as a check-gage against accumulated snow at the key snow-survey course at Soda Springs Station. During the past winter comparison was begun

Close observation of the snow-cutter reveals that it will not penetrate frozen snow or ice without heavy pressure even when twisted but will do so readily if the snow is moist, thus evidently permitting lateral movement of the crystals. When the cutter is rotated, the snow clogs the cutting faces and reduces the cutter to a chisel.

The metal must be made softer to permit sharpening the teeth in the field and the points of the teeth must be longer. Their faces should also approximate a spiral to elevate the ice-dust

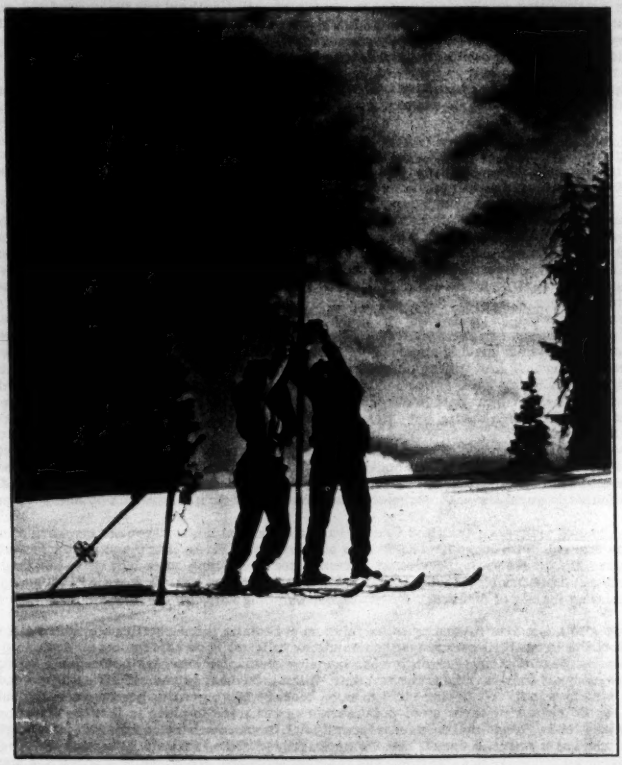


Fig. 14--Mount Rose snow-sampler in action
(Photograph by W. J. Herz)

Fig. 15--Experimental design of ice-cutter based on ship's auger (end of spiral should terminate in a narrow chisel in place of the semi-circle; lateral fins projecting downward from chisel might keep cutter true to its initial position)

above the cutter. Tests will be conducted in a cake of ice to simulate extreme conditions. An experiment once made for the Zurich Glacier Commission indicated the possibility of penetrating 1-1/2 inches of clear ice. Such depth is rare in snowfields. The need of bringing up the core makes the problem difficult, especially since the ice will melt while being cut but will refreeze immediately above the cutter when released from pressure and imprison it like a fish in a cake of ice.

It is possible that a hollow auger can be constructed that will cut out the core of ice, particularly if it is at the bottom of the snow, and bring it up for weighing with the core of snow. It could be made of a square or flat rod of spring steel with cutting end sharpened and curved into a spiral with inside diameter similar to the inside diameter of the sampler cutter and the outside diameter equal to the outside diameter of the sampler-tube. The length of the spiral would be merely sufficient to penetrate strata of ice but the length of the driving rod would correspond to the depth of the snow-cover. Its general appearance would be somewhat as in Figure 15.

The Horton snow-sampler--Contrasting with the Mount Rose snow-sampler, as Dr. HORTON has said, like the original locomotive with the modern Mallet, is the first snow-sampler to be used at least in America. This was the invention of Dr. ROBERT E. HORTON, who weighed snow-cores in 1903-04 and prepared a map of the water-content of the snow-cover for New York State.

The sampler-tube consisted of an iron pipe drawn down at one end to a smaller diameter and sharpened to cut and lift the snow. The cores were then weighed in inches of water. This sampler was used at Utica, New York, when Dr. HORTON was hydrographer of the United States Geological Survey. If surviving, it would be a worthy museum exhibit. Strangely, the pioneers in snow-surveying in Maine (MIXER), New York (HORTON), and Nevada never knew of the work of the others until their own work was done. Snow-surveying must have been in the air.

The following quotation from HORTON [Mon. Wea. Rev., May 1905, p. 197] shows his instinct and pioneer method of preparing a snow-map for New York State from water-snow ratios at Utica and his realization that snow-cover must be applied to the water rather than to the calendar year:

"Utilizing the water-snow ratios for Utica, a map has been prepared showing by isohydral lines the depth of water stored on the ground December 31, 1903, throughout the State of New York, representing precipitation during the calendar year 1903, but which became available to feed the streams during 1904.

"A very large percentage of accumulated snow subsequently appears as runoff in the stream, and it will be seen at once that in this locality the difference in water held on the ground as accumulated snow at the beginning and ending of any year, may be several inches--an important disturbing element in any attempt to correlate precipitation and flow of streams by calendar years."

Snow-course markers--Utah and Oregon have specialized in snow-course markers of steel pipe set in concrete with appropriate markers and painted in bands of red and yellow to make them conspicuous. If exposed to the possibility of being used as rubbing posts by cattle, they are protected by a mound of stone at the base ("steel pipe does not mind cattle rubbing"--R.A.W.). The pipe, consisting mainly of discarded boiler-tubes, was originally inexpensive.

Replying to a question regarding materials and especially the durability of steel, R. A. WORK, in Charge of the Oregon Snow-Surveys, comments as follows:

"There is more than one reason for our favoring steel-pole markers in Oregon. First, on some snow-courses there are no trees or other suitable landmarks and either steel or wooden markers need to be set. We prefer steel to wood because of its greater permanence and individuality. A second reason we favor steel-pole markers over trees in place is that the utilization of trees in place tends then to make the exact location of the snow-course contingent upon availability of natural markers, whereas we felt that the snow-course should be exactly located with regard to terrain, freedom from drifting, melting, etc. Of course, where trees are in place at the approximate proper places we use them, but find this proper combination not very often.

"Some of our steel markers have been in place for six years and show no signs of deterioration. I believe their life will be very long, but as Professor BOARDMAN suggests, their first weakness will probably occur at the Earth's surface. Where markers are on sidehills and consequently subject to the slow downhill movement of the melting snow-mass, we have learned to strengthen them by stubbing at the bottom with an extra six-foot section of pipe. The stub pipe and longer central steel pipe (two-inch) are solidly bound with plumbers tape.

"There are erected now in Oregon probably 500 steel-pipe markers, but the marking project is now discontinued until after the war, as it is impossible to secure pipe at any sort of a reasonable price."

Pack-frames--Performing the same function as the canvas carrying-case developed by PHILIP S. COWGILL and CARL ELGES is a duralumin pack-frame built by R. A. WORK that has individual places for each item of the snow-sampler to make any tool immediately available without removing the pack from the back. Its lightness and ventilation are additional prime qualities.

Snow-thermometers--The problem of snow-thermometers is keeping the bulb from coming in contact with melting snow, whose temperature necessarily cannot rise above 32°F. Since snow is porous and has a content of air, there should be the possibility of air-temperature slightly above 32°F, though the capillary water-film around the snow-crystals will be lower. There is also the danger of wetting the thermometers in handling or even of breaking them and the difficulty of placing and reading them in the snow.

For these reasons the thermometers used in snow-studies have been sealed in tubes somewhat smaller in diameter than the snow-sampler can cut and remove a core. After lowering the thermometer, the entrance of outside air can be prevented by a plug of snow.

The insulating air in the sealed tube necessitates leaving the thermometer in place for several minutes but also assures no or only slight change in its reading while being drawn up.

WALTER T. WILSON warns of the difficulty of using mercurial thermometers either in Sun, or in shade. He comments as follows: "Your comments on the observation of snow-temperature by means of sealed mercurial thermometers are appreciated. I have spent many, many hours on this problem. I do not deny that Professor BOARDMAN, on certain occasions, found little difference between Sun-exposed and shaded thermometers. My experience has ranged from no difference to as much as 10°, depending upon the wind and distance of the thermometer above the snow, as well as other factors. Sealing the thermometer alters the problem, but does not solve it. If there is any moisture in the snow, the temperature must be 32°F. There is so much heat in the mercury and glass in the thermometer that it may melt the snow in contact with it. A seal around the thermometer reduces the rate of heat-exchange between the snow and the mercury, thus requiring greater length of time to reach equilibrium. If an observer is careful and precools his thermometer to the temperature of the snow with successive 'dunkings' and takes plenty of time, good results are not impossible. However, care must be taken to avoid transfer of heat from the observer's body to the mercury either by contact or long-wave radiation. I agree that the metal back of a thermometer increases greatly the difficulty."

The greenhouse-effect of the sealed tube on the thermometer is a real danger particularly in very shallow snow or on the surface where the Sun's rays are effective. A screen at the ends of the tube to prevent the entrance of snow but permit the passage of air might serve as a partial control.

Air-temperatures on or immediately above the snow-surface are taken beneath a canopy of white muslin that can be adjusted to shade the instruments and yet permit free circulation of the air. By vertical tilting of the canopy at night, the instruments can be exposed to full radiation-effects and still be sheltered from the horizontal rays of the rising Sun.

The thermograph, if available, can be set on wood pegs just above contact with the snow. Metal backs for thermometers should be avoided as potential radiators of heat in favor of graduations on the glass tube itself. Unfortunately opaque metal is the basis of the thermograph and its container as well. To be mobile and adjustable for all types of measurements in snow, a full complement of thermometers should be provided.

Pigments--The study of the movement of melt-water in snow has emphasized the value of pigments. In his studies in Utah GEORGE D. CLYDE employed "fluorescein" to trace the path of the water and noticed that "during melting-temperatures the color quickly passed through the snow to the bottom; during freezing-weather, however, it remained in the snow-surface." In his study of ice-crusts and snow-melting in Washington, Dr. PHIL E. CHURCH used liquid dyes which he chilled to the temperature of the snow before sprinkling upon it.

Since there seemed to be a possibility that liquid dyes might penetrate the snow independently of melt-water, the Chairman in his snow-studies at Soda Springs Station experimented with dry dyes. The insoluble dyes, however, were too coarse to pass through the interstices of the snow-crystals and lay as a residue on the snow. They were, therefore, valuable only for indicating the snow-stratum when buried by accumulating snow.

Methyl-orange, which was soluble in water, indicated the movement of melt-water in new snow

vividly but did not penetrate old snow deeply nor widely. It had a slight effect in lowering the melting-point of the snow and accelerating melting at the surface.

Liquid dyes may be best provided their volume is almost infinitesimal as compared with their staining-power and the volume of snow being studied. On the other hand, a stain is desired that will descend only with the melt-water as it moves downward and will not permeate the capillary water sustained in the snow-cover. At times of melting, mountain snow normally freezes throughout its depth at night but becomes moist by day. Is this change due to the descent of melt-water or air circulation? This delicate determination may require a special dye.

Records--The current use of "water-content" by the Chairman and others in place of "water-equivalent" has been pointed out by WALTER T. WILSON as misleading if the phrase is logically defined. He suggests that the former term be used to express the melt-water actually present at the time in the snow-cover, and the latter to represent the potential water in the snow if melted. The terms "equivalent water-depth" and "water-equivalent" were used by HORTON as early as 1905 [Snowfalls, freshets, and the winter flow of streams in the State of New York, Mon. Wea. Rev., May 1905].

Ski-waxes--A wax-chart by Dr. HENRY I. BALDWIN for all types of snow- and ski-travel is published by the Woodstock (Vermont) Ski-Runners Club. This provides a long list of commercial waxes including paraffin and shellac with abundant opportunity for comparison by field-test.

Maps

The precipitation-maps of North America by Dr. CHARLES F. BROOKS, A. J. CONNOR, ROBERT G. STONE, and others for Blue Hill Meteorological Observatory are fundamental to snow-surveying in Canada and the United States. These maps are (a) mean annual snowfall (inches accumulated), (b) mean annual rainfall (inches), and (c) the percentage of annual precipitation that falls in the form of snow. Unfortunately Dr. BROOKS because of special duties does not see his way clear to develop a map of the snow-cover (inches water-equivalent) of April 1, but feels that others can prepare these snow-maps as well as or better than he.

W. W. McLAUGHLIN, Chief of the Division of Irrigation of the United States Soil Conservation Service, is planning a chart showing storage of water April 1, with the seasonal percentage of snow-cover at that date and potential water-resources for the season.

The United States Geological Survey is publishing stream-flow maps for monthly and longer periods and in cooperation with the Dominion Water and Power Bureau is publishing joint American-Canadian stream-flow reports. The Engineering News-Record is giving all of these maps wide publicity.

Of large background value in estimating the relative area at various elevations are the aeronautical charts provided for the Bureau of Air Commerce by the United States Coast and Geodetic Survey.

Publicity

Reports of snow-surveys throughout the winter and forecasts of stream-flow April 1, and even later, are made regularly by the Division of Irrigation of the United States Soil Conservation Service and various State Cooperative Snow-Surveys. Bulletins, radio broadcasts, and the press are joined in the service. The press eagerly publishes revised forecasts, for the public has become snow-minded.

Ski-weather forecasts have been limited as being an aid to the enemy but snow-depth and texture are permitted. New Hampshire has published three ski-posters in colors. Two of these, "Land of scenic splendor" and "The winter paradise" are reproductions of typical New Hampshire scenes by MAXFIELD PARRISH. It also has issued a "Winter map, 1941-1942 season."

Ski West, 1941-42, an illustrated prospectus of all the ski-courses in the Western States and Alaska, has been published by the United States Travel Bureau. Standard Oil Bulletin [November, 1941] calls attention to Mount Charleston's Ski-Run, near Lake Mead, under the title "Death Valley has exciting neighbors."

Newspapers and magazines are featuring the science of snow-surveying. Buick Magazine [January, 1942] carried "Ski-patrol" by MARGARET TIPTON WHEATLEY; Country Gentleman

[March, 1942], "Snow-harvest" by FRANK B. HARPER; Denver Post Rotagravure [March 1, 1942], "Frozen assets" by J. G. JAMES; Scientific Monthly [March, 1942], "The human side of snow: II--Sports and transport" by J. E. CHURCH; Life [April 20, 1942], "Engineers survey snow."

In technical literature other than transactions and reports are the chapters on (1) "Snow and snow-surveying; ice" and (2) "Glaciers" by Dr. J. E. CHURCH and FRANÇOIS E. MATTHES, respectively, in volume IX entitled "Hydrology" edited by Dr. O. E. MEINZER in the Physics-of-the-Earth Series of the National Research Council.

In popular appeal should be mentioned "Storm" by GEORGE R. STEWART, which was selected as a Book-of-the-Month.

The conservation of snow has actually become a polemic in an article on "Education for freedom" by Dr. ROBERT MAYNARD HUTCHINS [Harpers Mag., October, 1941]. Since Dr. HENRY I. BALDWIN, member of the Committee on Snow, was denied the privilege of answering on the ground that the communication was too late, his reply to President HUTCHINS is given below.

Education for freedom: An answer

Henry I. Baldwin

The October, 1941, Harpers Magazine contains an article entitled "Education for freedom" by Dr. ROBERT MAYNARD HUTCHINS, President of the University of Chicago, in which he points out some of the shortcomings of our educational system, as is his wont. As an example of the frivolity of modern science as he sees it, he makes the following reference to a paper by me presented before the American Meteorological Society at Durham, New Hampshire, in June, 1941:

"We can see now that our faith that science would sooner or later answer all questions has been misplaced. Everything that goes by the name of science does not deserve the reverence we pay it. Take, for example, the striking conclusions of the paper read at the last meeting of the American Association for the Advancement of Science by HENRY I. BALDWIN of the New Hampshire Forestry and Recreation Department. According to Science, Dr. BALDWIN found that early in the winter trees prevent snow from reaching the ground. He also discovered that snow in the forests lasts from one to three weeks longer than it does in the open." (Search of the issues of Science, May to October, 1941, fails to disclose any such reference. H.I.B.)

Unquestionably such conclusions by themselves are not worthy of reverence as great scientific discoveries, but the same might be said of a great many conclusions in scientific papers, removed from their context. Everyone knows how easy it is to make any report appear ridiculous by taking one or two sentences or phrases and citing them without further explanation. Indeed it is probable that equally enlightening conclusions might be gleaned from some of the research produced at the University of Chicago, yet presumably the investigations were worthwhile. Thus I am not so much concerned with the implied criticism of this particular project as with the method by which President HUTCHINS reasons that the results are unworthy of scientific notice.

Perhaps the fault was not entirely his, since his source of information was a brief abstract furnished as a routine matter for press-release by all who presented papers at this meeting. The abstract was limited by necessity largely to the main conclusions, without explanations. Owing to the preliminary nature of the report and due to the fact that some recent observations contradict previous findings, it was felt that only the most general conclusions could be offered. It is unfortunate that press-releases give at times very sketchy notions of the subject. The "paper" in this instance was not reduced to writing, but was presented orally from notes in the nature of a progress-report on the investigation. It was given at the invitation of the Secretary of the Society.

It is not my intention to defend the value of this investigation before scientists, nor to imply that it needs defense. Some readers of Harpers may wonder, however, with President HUTCHINS, of what use it is to study the effect of forests on interception and retention of snow. Of course, everyone has observed that trees catch part of the snowfall, but how much, and when? Do different types and ages of forest differ in this respect? How much longer does snow lie in the forest than in the open, and how does it differ in density and rate of melt from snow in the open? These and many other questions grew out of a study of the factors leading to the flood of March, 1936, in New Hampshire, and are some of the questions the present investigation seeks to answer. The flood-control surveys which have been in progress in New England during the last five years needed answers to these questions in order to complete their calculations. The United States

Forest Service, the Water Resources Board, United States Army Engineers Department, and many water-power companies have conducted snow-surveys and all have cooperated, taking observations at different places.

The observations reported in the case under discussion were made on the Fox State Forest in Hillsboro, New Hampshire, on 50 stakes, some under various types of forest, and some on the adjacent open land. Depths of snow are read on these stakes weekly throughout the winter in connection with travel for other purposes. The problem, which seemed very simple, has been found much more complex than supposed. Results in one year sometimes contradict those of another in some detail.

No cognizance would have been taken of this reference by President HUTCHINS, had not several well-known educators and scientists urged me to explain that snow-surveys, involving the effect of forests on snow-cover, are of vital importance in forecasting not only floods, but supplies of water for irrigation and power. The Committee on Snow of the American Geophysical Union and the closely allied International Commission of Snow and Glaciers act as coordinators of research and information in this field.

Fox Research Forest,
Hillsboro, New Hampshire,
January 7, 1942

Lectures, films, and photographs--Two popular lectures have been given, one by the Chairman at the Institute of Meteorology of the University of Chicago on Greenland and the other by CHRISTOPHER YOUNG before the Explorers Club on Skiing in Chile.

As previously noted, the films "Formation of snow-crystals in the mountains and in the laboratory of Japan", "Avalanche study in Switzerland", and the "Snow-survey" films by WALTER J. HERZ and R. A. WORK have been shown during the year at snow-conferences. Some have had a wide circuit. To these films should be added films on Tucker's spiral drive and the "Sno-motor"

A large collection of views of snow-landscape and details has been made by ERNEST MACK, Art Photographer, Reno, Nevada, representing the evolution of snow from autumn till spring. Other views showing elasticity and cohesion of snow have been taken by DICK LANDIS, Soda Springs, California, and of sunpits by VIRGIL D. SISSON, Los Angeles.

Publications--Publications, except in the form of transactions and reports, have been few, but Switzerland, England, Canada, New Zealand, India, Sweden, and the United States are represented. Some countries are cut off by the war. Reserves of transactions and reports are being accumulated for distribution as soon as the barriers are down and normal life returns.

In contrast to the usual summary of leading publications, some unpublished themes of unusual interest that have reached the Chairman's desk will be presented in its stead.

"Large snowflakes" by Dr. CHARLES F. BROOKS--On large snowflakes, I remember publishing a note in Bulletin of the American Meteorological Society (about 1924) on a case at Cape Horn--only a line or two in the discussion of some paper at a meeting of the American Meteorological Society. The flakes were three or perhaps four inches across. I have seen notes, I believe, in the Meteorological Magazine (London) on flakes as big as oak-leaves. I have seen flakes two inches across, not rarely either. Probably flakes get up to four inches across. They fall saucer-shaped. They are due to agglomerations of crystals overtaking one another at temperatures only a little below 32°F, so that the pressure of contact is sufficient to melt the points of contact, yet the water immediately refreezes. Heavy precipitation (intense rate) favors large flakes, also rather quiet air. The fluffiest snows come in weather too cold for flakes to form except by the enmeshing of the points of complex crystals.

I found in the Bulletin of the American Meteorological Society of May, 1931 [p. 95] the following brief note on some large snowflakes: "On March 31, 1931, great snowflakes fell for a half-hour in East Central Massachusetts, during the transition-phase from snow and sleet to rain in a coastal storm. The flakes averaged about an inch across, the largest measured were from 1-3/4 to 2-1/2 inches long. Each flake made an appreciable addition to the thin snow-cover."

"Minimum temperature of air compatible with melting snow" by WALTER T. WILSON--I wish to comment on a subject that has been receiving the Committee's attention recently, namely, the minimum temperature of the air compatible with melting snow. As I stated in a paper at Pennsylvania State College, there is great danger of noting a phenomenon under certain conditions, and

ascribing a universality to it which the evidence fails to justify. I have no doubt that this is the case with the question of minimum air temperatures concurrent with melting snow. I have observed air-temperatures in the forties over a snow-cover that had no appearance of melting. I have observed air-temperatures in the twenties over snow that was melting. These wide limits depend upon conditions which can and do occur frequently in any area.

In examining this question it is necessary to consider all the causes of melting. The three most significant sources or agents of heat are radiation, convection of heat from warm air, and the heat transferred by the change of state of water-vapor in the air. Radiation is influenced by the net result of solar radiation, albedo of the snow, and long-wave radiation to and from the snow. Convection of heat from warm air takes place at various rates, depending upon the degree of turbulence, but the critical temperature is and must be 32°F for this mode of heat-transfer. Heat transferred by the change of state of water-vapor takes place at various rates, depending upon the degree of turbulence, but the critical temperature is 32°F for the dew-point. With dew-point above 32°, snow will gain heat from the heat of vaporization of moisture condensed on the snow-surface. With the dew-point lower than the temperature of the snow-surface, evaporational cooling occurs. Air-temperature is a very poor index to heat-transfer by radiation. Still air, with a temperature of 30°, will not prevent the Sun from melting snow. I would not recommend computing degree-days on the basis of 30°F, but snow can melt by radiation with the ambient temperature less than 32°. This is not a stable condition, because it requires a superadiabatic lapse-rate. However, during a day having a mean temperature as low as 20°, there may be sufficient diurnal variation for melting to take place during the warm part of the day. Thus, in speaking of a temperature-base, one must consider the difference of purpose and meaning between momentary temperature and a daily mean.

Assuming no net heat-gain by radiation, consider the case of air having a dew-point of 15° and a dry-bulb temperature of 40°. Under these conditions the snow would not melt, because the heat lost by evaporation of vapor from the snow is not exceeded by the heat-gain from the warmth of the air. The theoretical maximum temperature compatible with non-melting snow, under these conditions, is 51°F, at sea-level. At higher elevations, with thinner air, the temperature may be greater than 51°, and still involve compensation by evaporation if the air is dry enough.

It must be emphasized, in connection with problems of heat-transfer, that the temperature-gradient is the important factor, the temperature at any one point being rather insignificant. In the case of melting snow, the air-temperature at the snow-surface is and must be 32°F where the air is in contact with the snow. The temperature, at the same time, might be 36° at a foot above the snow, 40° at four feet, and 45° at 12 feet. I have made some interesting observations of the temperature-gradient at various heights above the snow. I urge others to do the same thing as well as to note the effect of the wind on the gradient, shielding or shading the thermometers. I would suggest using a shady place, and mounting a few thermometers, one above another at various heights above the snow.

A sealed thermometer is a poor instrument for measuring air-temperatures. The exclusion of air from contact with the thermometer-bulb causes what is known as a "green-house effect" Radiation from the Sun penetrates the enclosure and heats the mercury. I know that the mercury reflects some of the radiant energy, and that it is also radiating as a black-body. However, there is no reason for assuming that these effects exactly compensate for the radiant-heat gain, or even approximate it. I have wished that mercury could be made to have the same albedo as snow (which observations made under my direction have shown, with a pyrheliometer, to vary from 45 to 85 per cent). If one could control the albedo of mercury, and could in some way include the effect of vapor-transport, a splendid index to snow-melting would result. The observation of 35° at Donner Pass might have resulted from this green-house effect, or from other causes, such as dry air, with evaporational cooling exceeding the other effects.

Pioneering

Hawaii and Alaska, our present scientific outposts, have acquired greater interest because of the war. CHARLES W. MILLER, Park Ranger in Hawaii, has been awaiting a snow-sampler to measure the seasonal accumulation of snow on the high peaks of the Island of Hawaii. ASHTON R. CODD, Hydrologic Supervisor of the United States Weather Bureau, has erected gasoline-drum collectors on the mountains of southern Alaska overlooking Juneau and Ketchikan to determine increase in precipitation with altitude. The Western tradition of initiative and adaptation under primitive conditions of transport resulted at least in initial success. A note on precipitation-gages in Alaska is of interest.

Seasonal-storage precipitation-gages in Alaska

Ashton R. Codd

During recent years the United States Weather Bureau has, from time to time, reported the progress made in the measurement of snowfall by installing windshields around rain-gages and

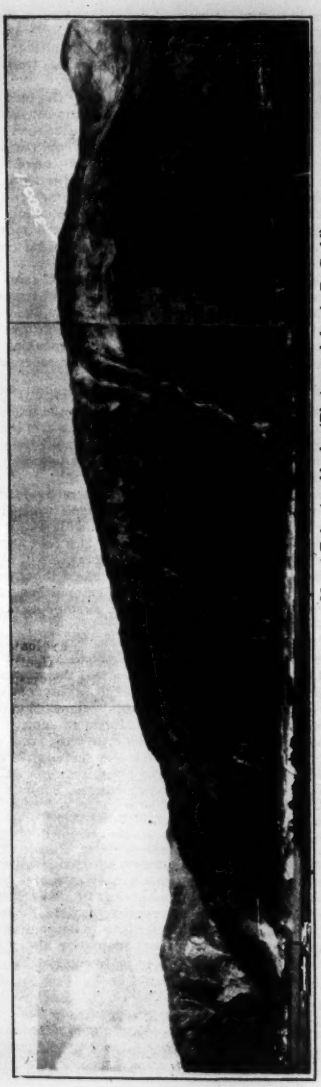


Fig. 16.--Storage-precipitation gage, Mount Roberts, Alaska (Photograph by A. R. Codd)

placing calcium-chloride solution in the receiver. This method of operating recording and non-recording rain-gages has proven very successful throughout the Western States, particularly in those latitudes where extreme low temperatures are encountered.

Early in the spring of 1941 an interesting problem in the measurement of precipitation along the southeastern coast of Alaska came to the Weather Bureau through the Forest Service from the Department of Interior. Investigations relative to water-power supply along the humid coast of Alaska had been in progress. From a report of a climatological survey made by Dr. JOHN B. LEIGHLY, Geographer at the University of California, it was brought to the attention of the Forest Service that there was a conspicuous lack of precipitation-data other than at seaboard towns. It was recommended that some attempt be made to obtain measurements at elevations as high as possible and at locations accessible by foot from a town or base of supply. The measurements were to be made as frequently as possible--at least monthly during the open season of the year and the winter precipitation was to be held in storage if possible and measured in the spring.

The Forest Service and the Weather Bureau collaborated in selecting localities for the test-gages. Mt. Roberts (Fig. 16), which rises to an elevation of 3,800 feet south and east of Juneau, Alaska, was selected as one locality, and Deer Mountain (Fig. 17-A), which rises to an elevation of 2,900 feet south and east of Ketchikan, Alaska, was selected as the second locality. It was planned to place gages at two elevation-zones in both localities, namely, 1,800 and 3,600 feet if possible. Timber-line in Southeastern Alaska is at elevation approximately 1,800 feet. With representative measurements at sea-level, 1,800 feet, and 3,600 feet, a close approximation could be applied to other localities.

Some previous measurements during past summers had been made with standard eight-inch rain-gages at these elevations. These fragments with the year-round Weather Bureau records at Juneau and Ketchikan were the only available data from which to compute the probable precipitation that might occur at the higher elevations during the winter months of October to April. During those months the gage would be unattended. In comparing these data it became evident that an estimated 200 inches of precipitation (water-equivalent) could very easily occur at these higher elevations during the winter. It would be necessary therefore to store this volume of water and keep it from freezing until spring when it would be measured. The measurement of this volume of water presented its own problem, inasmuch as 200 inches of water would weigh in the neighborhood of 365 pounds. A scale or measuring-device or system would

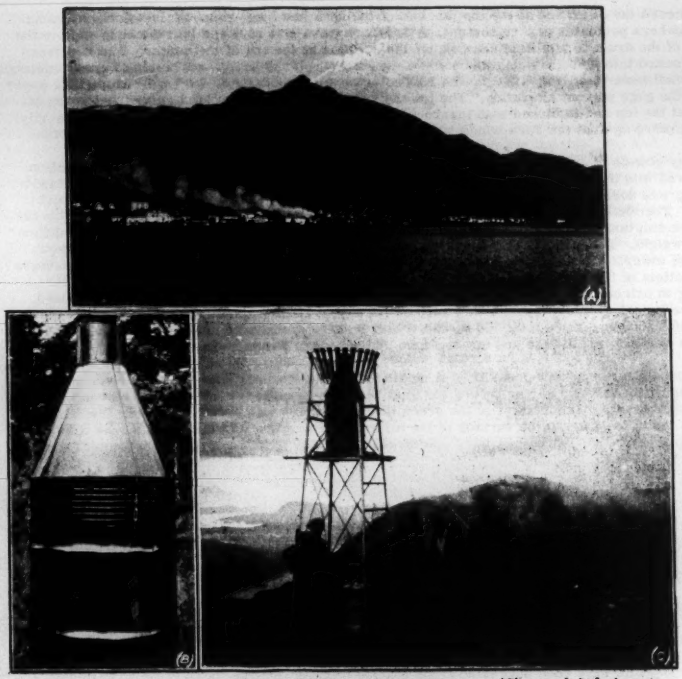


Fig. 17--(A) Deer Mountain, Alaska; (B) 55-gallon storage gage; (C) completed storage gage, Mount Roberts, Alaska, 3,600 feet
(Photographs by A. R. Codd)

have to be devised to cope with this situation. Due to the depth of snow, supports would have to be constructed to keep the gages from being buried. With these facts and problems in mind, together with past experience as a guide, the following plan was worked out for the first season's experiment.

The tower- or support-problem was readily solved by deciding to use the regular Weather Bureau angle-iron tower-support with the ALTER shield. This dispensed with considerable design and construction-work. Several of these ready-cut, knock-down towers, 15 feet tall, were in stock and ready for shipment. There still remained the problem of finding a receiver of sufficient size to hold the estimated 200 inches of precipitation together with sufficient volume of calcium-chloride solution to protect this quantity of water from freezing at temperatures as low as -10° F. Two hundred inches of precipitation will make 43.5 gallons of water and with 50 pounds of calcium chloride dissolved in eight gallons of water to give a solution of 33.4 per cent, the total volume would equal approximately 55 gallons. Upon measuring a standard 55-gallon oil-service drum it became apparent that one of these drums could be rebuilt into a precipitation-gage that would fit standard tower-supports and be of sufficient capacity to accommodate the estimated quantities (see Fig. 17-B). These 55-gallon receivers have an eight-inch diameter neck, 24 inches tall, held at the bottom by a metal collar welded to the top of the drum. A cone-shaped metal false-work was fastened down around the neck and over the outer edge of the drum to prevent snow from stacking up on the drum-shoulder. These pieces are removable but made water-tight where the

neck entered the drum and at the top junction of the neck and cone-shaped false-work, by using soft plumbers permatex gasket-cement. A 3/4-inch valve was screwed into the bung-hole in the bottom of the drum to facilitate drawing off the solution at the end of the winter. The receivers were blocked into place on a plantform of two- by six-inch planks which was bolted to cross-members of the steel tower (see Fig. 17-C). The ALTER-type windshield fitted very well around the upper part of the gage without alteration. The towers were guyed with four No. 9 galvanized wires attached at the top and tightened with turnbuckles. These guys were installed to brace the heavily loaded towers against the Taku winds which descend from the Taku Glacier with terrific force.

Fifty pounds of calcium chloride and eight gallons of water were weighed, put into solution and poured into the drum. A pint of turbo oil was weighed and placed over the solution. This weighing was done on a spring-balance with a scale of inches of water rather than pounds and ounces. The total water-equivalent placed in the gage amounted to 64.66 inches. The plan is to weigh the solution piece-meal again in the spring and ascertain the precipitation from the difference in weight. To facilitate this operation an adjustable weighing-bracket was attached to one leg of the tower. A short piece of garden-hose was stored at each gage for fastening to the valve on the bottom of the drum. With this hose the solution can be led into a smaller receiver for weighing in batches small enough so that the capacity of the scales, 22 inches, is not exceeded. This piece-meal weighing-system was adopted because a beam-balance of sufficient accuracy to weigh the last ounce of the total 500 pounds would be too expensive to attach to each gage, let alone its difficult installation and maintenance under severe weather-conditions.

There appeared to be a possibility of employees of the Weather-Bureau offices visiting the gages during the fall and spring before the final season was closed; consequently a means of taking an approximate measurement of the precipitation on these visits was arranged. The distance from the top of the gage to the surface of the oil over the solution was measured at the time of charging. If this distance is measured on occasional visits, a close approximation could be made of the amount of precipitation between the dates of measurement. The volume of the drums, in inches of precipitation, was computed on a chart-diagram.

The details of construction after the material arrived in Juneau and Ketchikan consisted largely of the arduous task of packing the towers, drums, and supplies up the mountains. This was accomplished on the backs of the crew as pack-animals were not available. At Ketchikan, the angle-irons of the tower which were being delivered to the mountain top by plane fell into the fjord, necessitating the construction of an eight-foot tower of timber.

These large storage-gages are an attempt to supply the need for securing the precipitation during the winter season at an unattended location. The gages and method of measurement are entirely experimental and have been made as simple as possible to suit the localities in which they are located. If it were possible to obtain these measurements from snow-survey courses, that method would have been suggested. The marine climate of these localities always presents the danger of losing the snow-cover prematurely and causes the great bulk of precipitation to occur in the form of rain. Recording-gages at the Weather Bureau stations at Juneau and Ketchikan will provide the details of the total precipitation.

It is hoped that this method of measuring the seasonal precipitation in isolated locations, where attendance is not available, will be of assistance to other engineers and niphometrologists. Whether or not these gages would be successful in the Cascades or Sierras, where large volumes of wet sticky snow are prevalent, is another problem but where the snow is dry or the bulk of the precipitation is in the form of rain there is every reason to believe the gages will operate successfully and that the seasonal precipitation as measured will be relatively correct.

U. S. Weather Bureau,
Washington, D. C.

Weathered snow

Figures 18, 19, and 20 record striking but inevitable phenomena in the physics of snow. Their counterpart in lesser magnitude can often be seen by the observant eye.

Although the snow in Figure 20 was called originally nieve penitente (penitent-monk snow) because of its frequency in the High Andes, it also occurs on the high peaks of Hawaii and North America as well as in the Himalayas. Do sunblades survive their season? The photograph was taken August 3.

The bowed white forms to the devout South American native immediately suggested the penitent monk, but to the Antarctic explorer they suggest penguins.

Honors--The Central Snow-Conference at its meeting in December, 1941, signalized the maturity of snow-surveying by giving the Chairman of the Committee on Snow a citation of appreciation and confidence.

This citation was immediately "dedicated to the Nevada Agricultural Experiment Station and particularly to Director SAMUEL B. DOTEN, whose initiative made possible the inception and progress of the work." In this should be associated President JOSEPH EDWARD STUBBS of the University of Nevada, who believed farther than others saw, PAUL M. NORBOE, Chief Assistant State Engineer of California, who gave snow-surveying continuing life in its darkest days, and Governor EMMET D. BOYLE of Nevada, who created the first State Cooperative Snow-Survey.

But associated with snow-surveying like atmosphere are scores whose personality is inseparable from the work. These, like MIXER and HORTON, reach from the earliest days and from the far places of the Continent. To all of them the citation belongs.

Deaths--Death seems to have kept distant from the inner ranks of snow-scientists and workers the past year. Of those in remoter touch, must be mentioned MORLEY MURPHY, legislator of Nevada, who attended the first Snow-Survey Conference in 1933; JOSEPH JACOBS of Seattle, who accepted service on the Regional Committee of the Section of Hydrology; and ARTHUR NEWELL TALBOT of the University of Illinois, who developed the TALBOT formula for determining the maximum rates of rainfall. To these should be added HARRY W. REPPERT, Nevada Assistant State Engineer, who was long a member of the Western Interstate Snow-Survey Conference and a supporter of cooperative snow-surveying.

Fig. 18--Breakdown of snow-crystals on surface of snow (the "ice-spray" is miniature), Soda Springs, about 7,000 feet, March 29, 1942
(Photograph by Ernest Mack)

The war

The war's dislocation but the high resolve of the civilian members to carry on is voiced by LE ROY K. SHERMAN, former President of the Section of Hydrology: "This year hydrologic research will be more or less of a war casualty. Still some of us old codgers who will not be accepted in either the Army or in the shops, should be salvaged as a useful corporal's guard to carry on scientific work."

Appreciation--Appreciation is again expressed by the Committee particularly to the Nevada Agricultural Experiment Station and the Federal Office of Experiment Stations that have provided clerical assistance and opportunity for cooperation, and to the various organizations that have

Fig. 19--Cornice snow on roof, Soda Springs, 1942; cohesion and elasticity of snow give snow-cornices their stability
(Photograph by Dick Landis)

Fig. 20--Dessicated snowfield with sunpits almost entirely vanished leaving sunblades standing alone, Piute Pass, Sierra Nevada, 13,000 feet
(Photograph by Virgil D. Sisson; kindness of Chester Versteeg)

shared in the Committee's work. The cooperative spirit of all interested in the fields of snow and ice is remarkable.

The Chairman personally is under still deeper obligation to the ideals of the Nevada Station that is sharing in a large way with him in the Presidency of the Section of Hydrology during the coming triennium.

Nevada Agricultural Experiment Station,
Reno, Nevada, July 1, 1942

APPENDIX A--LIST OF CURRENT PUBLICATIONS ON SNOW AND ICE

Ralph W. Burhoe and Horace P. Boardman

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SUPPLEMENT--ICING IN THE ATMOSPHERE

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REPORT OF COMMITTEE ON RAINFALL, 1941-42

Merrill Bernard, Chairman

The Research Committee on Rainfall is comprised of the following members: Merrill Bernard (Chairman); W. W. Horner; W. G. Hoyt; J. B. Kincer; Carroll F. Merriam; Thorndike Saville; L. K. Sherman; and C. W. Thornthwaite.

The year 1941 is believed to have brought to a temporary close an era in which precipitation, among the other hydrologic factors, has attained an indispensable place in design-methods. This improved status is reflected in a greatly augmented network of observation-stations, many of which are equipped with recording rain-gages. The most heartening encouragement is found in the determination on the part of the Engineer Department of the Corps of Engineers, and other agencies having the responsibility for the Nation's flood-control program, to prevent, if possible, a break in the continuity of precipitation-records throughout the War years ahead. Progress in the observation and analysis of rainfall is reported below.

Rainfall-observation stations--Additional stations were established under the cooperative hydrologic network program of the Weather Bureau, the Corps of Engineers, and the Department of Agriculture as follows: Five hundred recording rain-gages distributed over the United States, but principally along the Atlantic Seaboard and west of the Rockies; 50 non-recording gages, mostly at snowfall-stations in the far West.

This brings the total number of recording and non-recording stations in the hydro-climatic network to about 1,650 and 350, respectively. In addition to the recording stations operated by the Weather Bureau under the cooperative program, there are about 850 additional recording-gage records included in the hydrologic bulletins issued at the Weather Bureau regional centers from gages operated by other agencies independently of the network program. Records from approximately 1,900 non-recording gages are included in the hydrologic bulletins which are not published in Climatological Data Bulletins.

There was a net increase throughout the year of approximately 200 non-recording cooperative stations in the established climatological network of the Bureau.

The Division and District Offices of the Engineer Department, Corps of Engineers, have a number of rainfall-stations in basins under study as flood-control projects which are supplemental to the nationwide network. Each Engineer District has now one or more small experimental watersheds on which rainfall-runoff relationships are being determined.

Additional rainfall-stations have been reported to the Committee as follows:

Agency	Recording	Non-recording	Location
Bureau of Reclamation	...	7	Near Pueblo, Colorado
Los Angeles County Flood-Control District	3	6	Los Angeles Area
International Boundary Commission (United States and Mexico)	33	17	Southern Texas, below El Paso
Soil Conservation Service (Hydrologic Division)	8	...	Experimental area of Mexican Springs, New Mexico

The Soil Conservation Service reports that 40 non-recording gages at Coshocton are being discontinued or replaced by recording gages.

The field-offices of the Geological Survey have established gages in southern Florida and Santa Barbara County, California, to supplement the existing network in surface and ground-water studies.

A. S. FRY, Head Hydraulic Engineer of the Tennessee Valley Authority, reports the establishment of 41 precipitation-stations, 11 of which are equipped with automatic rain-gages, six with radio reporting devices, and 24 with standard non-recording rain-gages. There are now in the Tennessee Valley 491 precipitation-stations of which 350 are operated by the Authority, 94 by the Weather Bureau, and 47 by other agencies.

The Tennessee Valley Authority is engaged in the hourly analysis of recording-gage records

and in the correlation of rainfall, watershed-characteristics, and stream-flow for selected slow periods. The development of an attachment which will permit the use of the recording-gage chart for seven days by offsetting each day's record is in progress.

There were, undoubtedly, a number of stations established during the year which were not reported to the Committee, but from which records are obtainable from the usual sources for such data.

Hydrologic research-projects--The Soil Conservation Service, Climatic and Physiographic Division, reports progress in its study of rain-gage spacing, based on data from the Muskingum Project. The Soil Conservation Service has prepared tabulations of rainfall-intensity for 5-, 10-, 20-, and 30-minute intervals for 16 first-order Weather Bureau stations in the Middle West. Similar tabulations for 1-, 2-, 4-, 12-, 24-, and 48-hour intervals are in preparation. Frequency-distributions of all rainfall-intensities are prepared for each month and the seasonal variation in probability of high intensities is being studied. Two studies of time-interval between rains (drought) have been completed.

The International Boundary Commission reports progress in investigations of similar nature on the rainfall of the Lower Rio Grande and Guaymo Arroyo in South Texas.

The micro-climatic studies of the Muskingum Basin in Ohio are continuing.

In connection with the flood-control surveys of the Department of Agriculture, records from recording rainfall-gages were analyzed by five-minute intervals to obtain maximum storm-intensities and the distribution of the various intensities throughout the storm-periods. The records analyzed were for 13 stations widely scattered through the country from Vermont to Utah. In addition, records for Utah were analyzed to determine the areal extent of intense storms. The results of these rainfall-studies are used to calculate runoff for small drainage-areas by an application of the infiltration-capacity theory. As the drainage-areas selected for detailed study are often as small as 30 square miles, recording rain-gages are installed during the survey-period to supplement the records obtained from the Weather Bureau's cooperative network.

The Forest Service through its operations as well as its research organization has continued to maintain many rainfall-stations in order to forecast forest-fire danger and to study the effect of forests on stream-flow. During the past year intensive investigations of rainfall-interception by forest-vegetation, involving many measurements of rainfall, were conducted in Colorado.

Organization of storm-rainfall--This cooperative project between the Engineer Department of the Corps of Engineers and the Hydrometeorological Section of the Weather Bureau is continuing. Major storms of the past few years have been added to the 1,400 storms of record originally selected for study.

The immediate purpose of the storm-studies has been the estimation of critical duration-depth rainfall relationships for specific drainage-basins, to be used in determining spillway-specifications for large dams. However, the eventual utility of the data compiled is much greater. Following is a partial list of applications to which the ultimately organized storm-data may be put:

(a) The maximum average rainfall-intensity at each observation-station recording excessive rainfall, for periods as short as 6 to 12 hours
(b) Accumulative contemporaneous rainfall for all stations within the storm-area
(c) Mass-rainfall curves representing the average depth and areal distribution of contemporaneous rainfall
(d) Depth-duration curves representing the maximum average depth of rainfall, for specific periods of time and for specific areas
(e) The minimum area over which a certain volume of precipitation actually occurred in various periods of time

Hourly rainfall-data tabulations--This Work Projects Administration Project under which hourly rainfall at all first-order stations is being tabulated has progressed rapidly and is expected to be completed by June, 1942. It is planned to add to the rainfall-record of the first-order stations the daily rainfall-durations and amounts at certain of the older stations for periods prior to the beginning of autographic records.

Papers and reports--Among the literature of the year, there have been the following timely bulletins:

The International Boundary Commission has released an index of all known rainfall-records on the Rio Grande Watershed below El Paso, Texas, in the United States and Mexico, 1850-1940.

The Department of Agriculture [Hydrologic Bull. No. 1] presents the basic hydrologic data collected at the North Appalachian Experimental Watershed near Coshocton, Ohio, for the year 1939. This is the first of what will be a series of Annual Bulletins of this Soil Conservation Service project. Both amounts and intensities of rainfall are given, in addition to runoff. Similar bulletins are now in progress for the projects at Waco, Texas, and Hastings, Nebraska.

Among the technical papers on rainfall published during the year coming to the Committee's attention are:

"Surface runoff determination from rainfall without use of coefficients" by W. W. HORNER and S. W. JENS

"Method of predicting runoff from rainfall" by RAY K. LINSLEY, JR. and WILLIAM C. ACKERMAN

U. S. Weather Bureau,
Washington, D. C.

REPORT OF COMMITTEE ON INFILTRATION, 1941-42

G. W. Musgrave, Chairman

The membership of the Committee remained unchanged during the year and consisted of H. F. Blaney, H. L. Cook, G. A. Hathaway, R. A. Hertzler, W. W. Horner, M. R. Lewis, G. W. Musgrave (Chairman), and W. N. White.

As noted by SHERMAN in a communication to the Committee, the year 1941 witnessed some important developments in the field of applied infiltration: "(a) Recognition of the basic usefulness of the f-curve, the progression-curve of infiltration-capacity; (b) the first signs of agreement upon methodology for utilization of infiltration; (c) the presentation of the infiltration-theory to the engineering profession. Much of this progress has been due to HORNER for his papers before the American Society of Civil Engineers. SHERMAN and HORNER, working on parallel but entirely independent lines, have arrived at the correlation between infiltration-capacity rates and the corresponding volumes of infiltration."

The year has also witnessed some very definite applications of the infiltration-concept in connection with the growing National War program and, while particularly directed toward airports, is not entirely confined thereto. It is not timely, however, to go into details and we are justified in merely noting that definite strides forward have been made.

One of the most interesting recent developments is the plan of the Illinois State Water Survey in cooperation with the University of Illinois Agricultural Experiment Station, the Illinois State Geological Survey, and the National Resources Planning Board encompassing the infiltration-concept in a comprehensive study of the ground-water resources in certain important areas in Illinois. This is probably the first time that direct measurements of infiltration have been incorporated as a definite part of the plan of investigation of ground-water and the course of the work will be watched with interest. The investigation is financed by a recent appropriation of the State Legislature.

Calls for information in regard to infiltration also increased during the year. BLANEY notes that these inquiries come from engineers and public officials and pertain to problems of drainage and flood-control as well as of irrigation. The time is at hand when all comparative information should be made available to other workers and, as suggested by BLANEY, this is an item on which this Committee would be justified in devoting some time to the compilation of available data pertaining to the infiltration of different soils, vegetal covers, and other conditions.

It is apparent from correspondence that similar inquiries have come to M. R. LEWIS who is giving particular attention to infiltration in connection with problems of irrigation.

During the past year, we learn from the Director, "The California Forest and Range Experiment Station has continued infiltration-work in connection with flood-control surveys and the regular forest-influences research-program. The results of infiltration-studies on a small watershed near Friant, California, to determine the application of infiltration-data to hydrologic analysis, and of studies conducted at the San Joaquin Experimental Range, to determine the influence of different intensities of controlled grazing on infiltration, are being analyzed preparatory to

publication. During the coming year the Station will give high priority to the infiltration-work now in progress in connection with its various runoff-plot, lysimeter, and watershed studies.

"Perhaps the most important accomplishment of the year has been the application of ROWE'S detailed procedure in evaluating and determining quantitative effects of various land-use practices in watershed-management. The procedure eliminates the use of coefficients and permits evaluation of the influences of individual site-factors within unit-watershed complexes of soils and cover or land-use. It also permits determination of the effects of given remedial treatments of areas within a watershed upon floods and stream-flow. To date the procedure has been employed in a preliminary report on the Russian River, and in the flood-control-survey reports of the Santa Maria and Santa Ynez Rivers by the United States Department of Agriculture.

"The results of the infiltration-work in California show that use or treatment of land is one of the most important factors influencing the infiltration-capacities of most soils. For example, removal of the natural vegetal cover by burning or overgrazing, and the resultant exposure of the soil to the beating effects of rain and the trampling of livestock, have caused reductions by as much as 90 to 98 per cent in the infiltration-capacities of some of the areas studied. In some agricultural soils the use of clean tillage and planting of certain row-crops have brought about reductions of more than 80 per cent in the infiltration-capacities. Type of vegetal cover is one of the more important of the environmental factors influencing the infiltration-capacities of soils. Studies comparing the infiltration-capacities of similar soils under different vegetation covers have shown differences in infiltration-capacities in excess of several inches per hour. In the application of infiltration-capacity data to the hydrologic analysis of western watersheds, it has been found that soil-depths, and the storage-capacities and drainage-characteristics of the soils and substrata are of extreme importance and in many instances are the limiting factors."

WILM advises, "Current infiltration-studies by the Rocky Mountain Forest and Range Experiment Station include some laboratory experiments on infiltrometers, but are largely devoted to field-measurement of the average infiltration-rates in experimental pastures and watersheds.

"The laboratory studies were designed to develop and test improvements in the application and measurement of artificial rainfall on infiltrometers of the types F and FA. As the tests are not completed, no results are yet available for publication.

"The field-experiments are being conducted principally on a series of six experimental pastures of the ponderosa-pine type. The purpose of these studies is to measure the influence of three different rates of cattle-grazing on infiltration and other watershed-factors. The type-FA instrument is employed, with some slight improvements designed to facilitate field-use of this infiltrometer. In each pasture 18 plot-locations are selected each year by randomization, with two plots in each of three plant-types within each of three areal strata. By this scheme sampling errors form a relatively small part of the variation between pastures which are treated alike.

"Aside from these measurements, a small infiltration-study is being conducted on three small watersheds (1 to 1-1/2 acres in area), to ascertain the relation between average infiltration-rates determined by means of type-FA infiltrometers and watershed infiltration-rates derived from rainfall- and runoff-records. Up to now the results have been negative, because no recorded storm has been intense enough to cause appreciable surface-runoff."

In a forthcoming paper by BORST and MUSGRAVE, it is shown that the variation in infiltration on a single site during the course of several years follows very closely the ratio of temperature to soil-moisture. It is believed that among the causes of seasonal variation in infiltration upon a given site-temperature and soil-moisture are often the most prominent.

SHARP and HOLTAN, in carrying forward the project under the direction of the Chairman of the Committee, had opportunity to make comparisons of natural and artificial rains upon plots 6 by 12 feet in size. This problem is too important to attempt drawing definite conclusions from meager data. It may be noted, however, that in the results thus far obtained on a site in Colorado, natural infiltration-rates were approximately one-half comparable artificial rates. These differences may be due to one of several causes: (a) Infinitely wide wetted borders in natural rains as compared to three-foot wide wetted borders during artificial rains; (b) differences in raindrop-sizes and/or velocities (impact); and (c) other causes not yet determined.

The same workers on the Colorado site found little or no relationship between antecedent soil-moisture and infiltration-indices of the Bresser soil. On the heavier valley-soil, Nunn clay-loam, the data indicate that there probably is an inverse relationship between antecedent soil-moisture and infiltration-indices.

These workers also completed a few studies of the rate of movement of subsurface gravitational water. This was accomplished by means of resistance-readings at frequent time-intervals upon Bouyoucos blocks well spaced in the profile. The data were subsequently confirmed by

photographs of the soil-section and show in this soil a rate of vertical movement of gravitational water about four times that of horizontal movement during a 24-hour period. Further investigation including a longer period of application, is planned since it is possible that during the 24-hour period horizontal movement had nearly reached its maximum.

The above data on rate of subsurface movement of gravitational water has a definite bearing upon the size of wetted borders around plots receiving artificial applications of water. A systematic study of this problem on the Colorado site indicated that little would be gained by having buffer-wetted areas wider than three feet.

One of the very interesting phenomena found on this soil is the tendency toward a slight increase in infiltration even in very long-continued applications (72 hours) of water. It should be noted that this soil has a substratum which is sandy in character and which is very deep.

Opportunities exist for more definite integration of the work of this Committee and the Committee on Snow. One of the items in which both Committees have interest is the conservation of precipitation. In this connection, Dr. J. E. CHURCH writes, "Close collaboration between the Committees on Snow and Infiltration is one of the inevitable developments. It should also extend to Underground Water." In the International Commission of Snow all three of these phases are represented. Doubtless in the Section of Hydrology collaboration of this kind is entirely feasible.

Appendix

Mr. SHERMAN states: "Temperature and f_c--When a number of f-curves are derived from different rainfalls, even though they relate to the same area and the same season, such f-curves or arcs of f-curves will not be of exactly the same form. There are some 24 variables which affect infiltration. Some of these variables are in operation even on the same plot and in the same season. However, the composite of these f-curves does not, in general, differ radically from any single curve. In practice it is too involved to attempt segregation of all of the factors which cause variation of f-curves. MUSGRAVE has indicated that temperature-variation produces marked effect on the values of f_c. Data on this are needed. Perhaps it would furnish more consistent f-curves than those based upon a single f_c for the entire season.

"Check on infiltration-methodology--The United States District Engineer's office at Little Rock, Arkansas, has recently tested and adopted the infiltration-procedure presented by SHERMAN and MAYER [Trans. Amer. Geophys. Union, Pt. III, p. 666, 1941].

"At times there has been some misunderstanding in the use of the C_b-(constant-base)diagram. Therefore the following: In the equation

$$C_b\,(f - f_c - 0.01) = \text{volume above the line } f_c \qquad (3)$$

the term $(f - f_c)$ is numerically equal to the total observed volume of infiltration during the period T; f_a or f_{av} = total volume divided by T. (Always use f_a if the data permit.) When the time period T is wholly to the left of PT (zero-time) by an amount t_1 the equation (3) becomes

$$C_b\,(f - f_1) = \text{volume above the line } f_c \qquad (4)$$

When $(f - f_c)$ or $(f - f_1)$ are fitted to a given C_b-curve, then the upper and lower ends of the hypotenuse will give the true position of f_c and f_1 and the time-position at the beginning and end of T.

"Both equations (3) and (4) mean that if C_b, derived from formula (1), is say 0.45, then the volume of infiltration above line f_c is 45 per cent of the total observed volume of infiltration."

Soil Conservation Service,
Washington, D. C.

REPORT OF COMMITTEE ON THE CHEMISTRY OF NATURAL WATERS, 1941-42

C. S. Howard, Chairman

The membership of the Committee during the past year was as follows: I. A. Dennison, National Bureau of Standards; C. S. Howard (Chairman), Geological Survey; C. S. Scofield, Department of Agriculture; D. G. Thompson, Geological Survey; and T. G. Thompson, University of Washington, Seattle, Washington.

SCOFIELD has continued his studies in connection with the salt balance in irrigated areas and has made progress-reports to interested parties concerning the salt balance on the El Paso Project, Wapato Project, and the Yuma Project. These studies are of great interest to those responsible for the operation of the projects and should be of considerable value to other projects

in indicating the volumes of water that may be necessary under certain conditions to insure proper drainage of the project.

T. G. THOMPSON has continued his studies on the chemistry of natural waters, particularly in connection with the studies of oceanography but this work has been curtailed to some extent because of war activities.

DENNISON has given some consideration to the relationship between the corrosivity of natural waters and the chemical composition. In order to enable engineers to predict from the chemical characteristics of a water the probable behavior of various metals and alloys used in contact with this water this work is being done as a part of the studies on the corrosion of metals conducted at the National Bureau of Standards.

During the year many demands have been made on the Geological Survey for information concerning the quantity and quality of ground-waters and surface-waters available in different parts of the country with particular reference to their availability and suitability for plans of defense and war production. In many fields of industry the chemistry of natural waters is of considerable importance and the information available from all sources has assisted in the proper planning of many of the new industries and for expansion of existing facilities.

The studies on the quality of the waters in the Pecos River Basin have been continued by the Geological Survey and one paper dealing with some of the results of these studies is being presented at this meeting under the title "Quality of stored water available for use in the Lower Basin of the Pecos River, Texas."

U. S. Geological Survey,
Washington, D. C.

REPORT OF COMMITTEE ON UNDERGROUND WATERS, 1941-42

David G. Thompson, Chairman

So many ground-water hydrologists are engaged on problems relating directly to the war that the usual annual inquiry for information as to projects that deserve review in the annual report of the Committee on Underground Waters brought relatively little response. It is in part for this reason, but also in part because the Chairman of the Committee is busy on war problems, that this report is shorter than usual.

There is, nevertheless, abundant evidence that principles of ground-water study that have been developed over a period of years are being put to good use in the effort to win the war. Since about September, 1940, the Division of Ground Water of the United States Geological Survey, for example, has reported on ground-water conditions at about 750 localities in the United States and foreign countries where military establishments, industrial plants for the production of war materials, or housing projects were being contemplated. Many of the reports were more or less routine and largely based on published reports or data in the files of the Geological Survey. However, a considerable number of special field-investigations have been made. In some of these it has been necessary to apply a strictly scientific approach to the more practical problems of the war need--perhaps, for example, to determine whether a large quantity of water, in excess of the average annual recharge, can be pumped for a vital industry for the period the war may be expected to last; perhaps to determine whether even a small quantity of water for a coastal lookout post may be obtained without danger of contamination by salt water; or perhaps to determine how much water can safely be obtained from an aquifer that apparently is extremely permeable, and will yield large quantities of water for a short time but the probable intake-area of which is not great, so that the water impounded in the ground-water reservoir would soon be exhausted if pumped at a high rate. Although not much can be said at this time in regard to the many problems that have been studied, it is believed that, when peace returns and field-data may be studied more leisurely, valuable information bearing on problems of ground-water hydrology may be found in the experiences of war. A single instance may be cited.

A large munitions plant is taking a huge quantity of water from shallow wells that are situated close to a large river. An analysis of the geological and hydrological conditions indicates that the wells could yield such a large quantity of water only if it is entering the ground essentially directly from the river. During the winter of 1941-42 the yield of the wells decreased considerably and the water-level in the wells declined. The question was raised as to whether the decrease in yield

was due to silting of the bottom and sides of the river, or to some other cause, perhaps, for example, to clogging of the well-screens. Ground-water hydrologists who were consulted suggested that perhaps the decrease in yield resulted from an increase in the viscosity of the water as the temperature of the river-water, and subsequently of the ground-water, decreased. Observations subsequently showed that the decrease in yield of the wells was proportional to the increase in viscosity of the water. It was therefore concluded that the situation probably was not as serious as first considered and that the yield of the wells would increase as summer approached. Recent observations have shown, as the temperature of the river-water has increased, an increase in yield of the wells, bearing out this conclusion. There remains, however, the possibility that a decrease in yield could occur for other reasons, as suggested above. Observations at this plant are being continued.

The following statements have been received in regard to investigations of other organizations.

HARRY F. BLANEY: The Division of Irrigation, Soil Conservation Service, in connection with irrigation and consumptive use of water-studies, is continuing measurements of ground-water fluctuations in a number of wells in the San Luis Rey Valley and San Jacinto Valley, California, in cooperation with the California State Division of Water Resources and the United States Geological Survey. Water-spreading studies are also being continued in several sections of California.

As part of a cooperative drainage study of irrigated lands in the Imperial Irrigation District, California, observation-wells were established by the Division of Irrigation in typical farms drained by tiles, and measurements were started on ground-water fluctuations in 1941.

F. H. LAHEE states, in regard to studies of ground-water in oil-fields, that much is being done in regard to methods of handling and disposing of such waters as are troublesome to the oil-producers, but the information thereon is largely confidential. Also, in connection with the subject of ground-water in oil-fields, reference may be made to a report published by the United States Bureau of Mines in October, 1941 [Research Investigation 3595], entitled "A laboratory study of water encroachment in oil field sand columns" by FRANK G. MILLER.

EDWARD B. BURWELL, JR. reports that the Ohio River Division of the Corps of Engineers has recently made studies of water-table conditions in certain limestone-areas in connection with reservoir-studies in the Cumberland River Basin in Tennessee.

Dr. A. C. SWINNERTON has submitted, as usual, an excellent statement on research on hydrology and physiography of limestone-terranes, which forms an appendix to this report.

At the meeting in 1937 of the Section of Hydrology, D. C. ASHMEAD presented a paper entitled "Water pumped from mines of the anthracite region of northeastern Pennsylvania," in which it was shown that large quantities of water enter the mines and must be pumped out. Further information on this subject is contained in a report of the United States Bureau of Mines (Information Circular 7175) entitled "Water problem in the Pennsylvania Anthracite mining region" by S. H. ASH, which was published in June, 1941. The report states that in 1939 the water pumped from mines in two counties in the so-called northern anthracite-field amounted to more than 78,483,000,000 gallons (an average of about 215,000,000 gallons a day). Possible methods of reducing this large pumpage of ground-water are considered briefly, but no obvious remedy is indicated.

In the report of the Committee on Underground Waters for 1940-41 [Transactions of 1941, p. 949] it was stated that fluctuations of water-level caused by an earthquake on December 21, 1939, on Celebes Island, in the East Indies, had been recorded in an observation-well in Florida, about 10,180 miles from the epicenter. It is necessary to correct this statement because the writer's attention has been called to the fact that, allowing for travel-time of the Celebes shock, the shock in Florida was recorded too early. The error in reporting arose in part because on the same day as the Celebes earthquake, and within a period of a few hours, two shocks occurred in Costa Rica. The information as to time of shocks was obtained from different sources and apparently the Chairman made errors in making time-corrections. The record for greatest distance at which an earthquake shock has produced fluctuations of water-level in an observation-well now apparently is that of the Turkish earthquake of December 26, 1939, which was recorded in a well at Honolulu 8,100 miles from the epicenter.

U. S. Geological Survey,
Washington, D. C.

APPENDIX A--RESEARCH ON HYDROLOGY AND PHYSIOGRAPHY OF LIMESTONE-TERRANES

A. C. Swinnerton

Activities in several organized research-programs have been interrupted first by defense-work and later by the war efforts. For example, WILLIAM M. McGILL of the Virginia Geological Survey writes: "... I have nothing of interest to report on work on limestone-terranes, physiography, or related fields in the Valley-Region of Virginia during the past year. Practically all of my time ... has been devoted to studies of water-wells and ground-water conditions in connection with the location and development of military camps, national-defense projects, and related activities. .... I hope to work up, later, a statement covering the results of such activities ... that will be of interest ... in connection with ground-water conditions ..."

Otherwise the situation is mainly one of "suspended animation", except for the publication, or preparation for publication, of earlier investigations. Late in the spring, ROGER F. RHOADES, leaving the staff of the Tennessee Valley Authority to join the Reclamation Bureau in Denver, completed several manuscripts relating to ground-water activity in limestone:

[1] Artesian conditions in the Lower Tennessee Valley, Econ. Geol., v. 36, pp. 490-511, 1941.

[2] Pre-Pleistocene initiation of deep solution in the Lower Tennessee Valley, Amer. J. Sci., v. 239, pp. 764-770, 1941.

[3] Pattern of ground-water flow and solution (with M. N. SINACORI), J. Geol., v. 49, pp. 785-794, 1941.

The basic concepts of the first were reported to the Committee on Underground Water two years ago. The remedial engineering works necessitated by the conditions leading to the conclusions of the second paper were mentioned last year. Briefly summarized the conditions at the site of Gilbertsville Dam include deposits of undisturbed sand of the Ripley (Cretaceous) formation at depths 100 feet below the river in solution-fissures. Mechanical analyses are relied on for the identification of the sand.

The third contribution is an analysis of the flow-pattern postulated by DARCY'S law as applied to the solution-dynamics of limestone hydrology. The conclusion is reached that "Although ... deep flow and solution are entirely harmonious with hydraulic principles, an important aspect of the problem of the optimum depth of ground-water flow and solution is the matter of adjustment of the subsurface circulation. As this adjustment becomes more perfect, deep flow and solution progressively diminish and flow and solution in the upper levels of the zone of saturation increase correspondingly. In the latter stages of the cycle, cave-formation probably occurs at higher levels by the concentration of lateral flow through high-level master-conduits."

Current work by the Tennessee Valley Authority is reported by B. C. MONEYMAKER: "Over the past year, we continued to accumulate data in regard to the location, size, extent and depth, of sub-river solution cavities in the Tennessee Valley Region. Although our construction schedules have been such as to permit little work on the data so accumulated, it can be said that, in general, we found cavities at much deeper elevations than in previous years. The deepest cavity known in the Valley to date is at Elevation-15 (285 feet below the surface) near Gilbertsville, Kentucky. Near Lenoir City, Tennessee, solution-cavities have been encountered well over 200 feet below the bed of the Tennessee River.

"Particular attention has been paid to the excessively deep and very narrow solution-cavities in the Fort Payne chert in the lower portion of the Tennessee Valley. Studies now in progress are throwing considerable light on the mode of origin of these cavities.

"Detailed studies are being made as to the depth of weathering in the siliceous rocks in the eastern portion of the Valley Region. It is found that weathering, as marked by rusty joints, the decay of ferromagnesian minerals, and zones of rotten rock, extends to depths comparable to the depths of solution in the adjacent limestone-terranes [see Bull. Geol. Soc. Amer., v. 52, pp. 1923-1924, 1941]."

Of the work of the United States Geological Survey, V. T. STRINGFIELD writes: "Investigation of ground-water in limestone in Florida and Georgia are being continued by the Federal Survey in cooperation with the Florida Geological Survey and the Georgia Division of Mines, Mining, and Geology. Also ground-water studies in the Coastal Plain of North Carolina started in 1941 in cooperation with the North Carolina Division of Geology include water-bearing formations which are limestone. The presence of limestone or marl interbedded with water-bearing sands as in parts of the Coastal Plain of North Carolina is of interest in the development of water-wells because many of the wells are finished without screens.

"It may be of interest to note that a paper entitled 'Artesian water in the Coastal Area of Georgia and Northeastern Florida' [Econ. Geol., v. 36, pp. 698-711, 1941] contains a brief description of the hydrology of the limestone which is the principal artesian formation in that area."

In last year's report the large yield of wells in limestone in Florida was mentioned. Since that time an artesian well has been drilled at San Antonio, Texas, with a reported yield of about 17,500 gallons a minute (about 25,000,000 gallons a day) from the Edwards-Georgetown Limestone Reservoir. This may prove to be the largest artesian well in the world.

At the Dallas Meetings of the American Association for the Advancement of Science one session of Section E was devoted to a symposium, jointly sponsored by the American Geophysical Union and the Geological Society of America, on the "Relation of geology to the ground-water problems of the Southwest." Of the eight papers presented three dealt with limestone hydrology or solution phenomena.

The papers presented at the Dallas Symposium appear in Part I of the Transactions for 1942 [pp. 5-56].

The hydrologic system of the Edwards-Georgetown Limestone Reservoir, reported by SAYRE and BENNETT, shows evidence of ground-water movement from the recharge-areas not only down-dip but also diagonally. This limestone reservoir is very productive, yielding artesian springs and wells which are among the largest known. The Pecos Basin, described by A. M. MORGAN, with its great thickness of limestones, gypsum, and halite, is supplied by a limestone aquifer. Circulation to the surface has dissolved vast quantities of salt and gypsum and is, according to MORGAN, responsible for the development of the Pecos depression. Solution of salt and anhydrite at depth by artesian circulation is shown by FRYE and SCHOFF to account for the sink-holes of the Meade Basin of Kansas and Oklahoma.

Reporting for the National Park Service, H. E. ROTHROCK, Acting Chief, Naturalist Division, Branch of Interpretation, writes: "A study of the underground hydrology of Chaco Canyon National Monument, New Mexico, was made by the writer, and a Service report is now in preparation. The study covered a portion of the southern flank of the San Juan Basin. It is not anticipated that this report will be given public distribution.

"A program of shallow water-well drilling was completed on the Island of St. Croix, Virgin Islands. A total of 33 wells was completed, 24 of which were adequate producers. Service reports on the geology of the drill-sites and the results of drilling have been prepared but no opportunity has been afforded for public distribution.

"A Service report on the feasibility of developing underground-water supplies on the Island of St. Thomas, Virgin Islands, was prepared."

In the more limited field of cavern-investigation some reports indicate work in progress. During the present semester one of Professor EDWARD L. TULLIS'S (South Dakota School of Mines) students is mapping Wild Cat Cave near Rapid City. This cave has been opened recently. It is hoped that the data on those problems not adequately covered in earlier publications will be secured from this study. The problems concern some breccias which do not seem to fit into the story as reported previously and also some pseudo-flowstone deposits.

J. HARLEN BRETZ'S comprehensive manuscript on caves, reported in preparation last year, is expected to appear as a special supplement to the Journal of Geology during the summer of 1942.

The National Park Service treatise on caves, prepared by J. VOLNEY LEWIS, is undergoing revision and there is still hope for its eventual publication.

The National Speleological Society has continued to show enthusiasm and growth. These are reflected in its activities including meetings, cave-trips, and improved quality of its publications. The compilation of a cave-catalogue together with a file of maps and other materials is a potential source of valuable information for scientific studies. On October 17-20, 1941, was held a field-symposium on caves and a principal address was given by CHARLES BUTTS on the development of deep caverns below the water-table. The Librarian of the Society is ROBERT BRAY (Route 2, Herndon, Virginia) and its President is WILLIAM J. STEPHENSON (Route 2, Richmond, Virginia).

Antioch College,
Yellow Springs, Ohio

REPORT OF COMMITTEE ON TRANSPIRATION AND EVAPORATION, 1941-42

J. Kittredge, Chairman

The Committee has the following members: T. C. Adams; N. W. Cummings; W. E. Davis; S. T. Harding; A. H. Hendrickson; I. E. Houk; J. Kittredge (Chairman); E. W. Lane; C. H. Lee; C. G. Rossby; T. Saville; C. A. Taylor; C. W. Thornthwaite; H. C. Troxell; and H. G. Wilm.

As the principal contribution for the report this year, Dr. HENDRICKSON has prepared the following statement on periodic sampling of soil-moisture as a means of arriving at losses of water by evaporation and transpiration. Several paragraphs of discussion and current developments follow his statement.

University of California,
Berkeley, California

DETERMINATION OF THE LOSSES OF MOISTURE BY EVAPORATION FROM SOILS IN A WATERSHED-AREA

A. H. Hendrickson

Studies on losses of soil-moisture by transpiration of orchard trees have been carried on at the University of California for many years. The results obtained have emphasized the importance of two soil-moisture constants--the moisture-equivalent and the permanent wilting-percentage. The moisture-equivalent is the amount of water retained by the soil against a centrifugal force of 1,000 times gravity, or about 1,000,000 dynes per gram, and is expressed as a percentage of the oven-dried weight of the soil. This determination is an arbitrary one and is affected to a large extent by the way in which it is made. The moisture-equivalent determination, as made in our laboratory, agrees closely with the field-capacity, or the amount of moisture retained by soil after the rate of downward movement has materially decreased, which usually takes place within two or three days, in most of the fine-textured soils, but not always of the sands. The permanent wilting-percentage is the moisture-content below which the plants cannot readily obtain water. It follows that the moisture above the permanent wilting-percentage is readily available to trees and other plants. Moisture above the moisture-equivalent is also readily available, but the moisture-equivalent may be taken as the upper limit of the readily available moisture, because in well-drained soils, the moisture-content remains above the moisture-equivalent for only a few days, following a rain or an irrigation. Movement of water after the soil has drained to the field-capacity is extremely slow.

The amount of water used by trees, when the moisture-content of the soil is reduced from the moisture-equivalent to the permanent wilting-percentage, plus that lost through surface-evaporation, is also the amount of water necessary to refill the soil-reservoir and to bring the moisture-content back to the moisture-equivalent. One method of finding out the amount of water necessary to bring the soil-moisture content back to the moisture-equivalent in plots when the readily available moisture has been exhausted, is to take soil samples a few days after a rain or irrigation. If the rain or irrigation has been measured, dividing the average penetration by the depth in inches of water applied gives the penetration per inch of rain or irrigation-water. From these data the total amount required to penetrate to a given depth may be obtained. As typical examples, an inch of rain or irrigation penetrates to a depth of about 12 inches in an Oakley sand at the permanent wilting-percentage, to about nine inches in a Fresno sandy loam and to about five inches in a Yolo loam.

Another method of finding the amount of water necessary to refill the soil-reservoir is by calculation, using the moisture-equivalent, permanent wilting-percentage, and the volume-weight of the soil. The best time for finding the volume-weight is shortly after the soil is at field-capacity, or when the soil in the tube remains as a definite core rather than when it breaks down as is the case with some sands. The samples for volume-weight are taken with a soil-tube on which one-foot intervals are marked. The diameter of the core is obtained by cutting disks of sheet lead (about one-quarter of an inch thick) and carefully measuring the diameters of the disks with calipers. These disks are easily cut, can be measured by external calipers, and show any irregularities in the edge of the cutting point of the tube. The soil-samples are dried and the dry weight divided by the volume of the core to obtain the volume-weight. The volume-weight is usually expressed as pounds per cubic foot of soil.

To convert the percentage of moisture on the dry-weight basis to the equivalent depth in inches necessary to refill the soil-reservoir, that is, the difference between the moisture-equivalent and the permanent wilting-percentage, the following formula is used:

$$\text{Amount of water (depth in inches) to wet one foot of soil} = [(\text{per cent moisture on dry-weight basis})/100] \times [(\text{weight in pounds per ft}^3)/62.4] \times [\text{depth of soil wetted in inches}]$$

As an example, the Fresno sandy loam has a moisture-equivalent of 11.2 per cent, a permanent wilting-percentage of 3.5, and a volume-weight of 90 pounds per cubic foot. The percentage of moisture required to raise the moisture-content of a 12-inch layer from the permanent wilting-percentage to the moisture-equivalent is (11.2 - 3.5) or 7.7 per cent. From the equation the amount of water (depth in inches) to wet one foot of soil is $(7.7/100) \times (90/62.4) \times (12) = 1.33$. In other words, each foot of Fresno sandy loam at the moisture-equivalent contains 1.33 inches of moisture available to plants, and when the soil has been reduced to the permanent wilting-percentage this is the amount necessary to refill the reservoir. This amount must be added to each foot of soil, say by rain during the fall and winter, before there can be any movement of water, on the surface or underground, to other areas.

In our experimental orchards, if the sampling is started before the trees or cover-crops have used much water, the initial moisture-contents show close agreement with the moisture-equivalent. As the trees use water, the moisture is extracted rather uniformly to the depth occupied by the roots, until the permanent wilting-percentage is reached. At the permanent wilting-percentage the extraction almost ceases. When plotted, the curves show a rather uniform downward slope until the permanent wilting-percentage is reached after which it is horizontal or nearly so. This marked change in slope occurs at the same moisture-content each year. Another method of determining wilting-percentage is by growing plants in containers holding a known weight of the soil, and determining the residual moisture-content when permanent wilting occurs. A more complete discussion of these soil-moisture characteristics is given in Extension Circular 50, of the California Agricultural Experiment Station.

We have frequently been able to predict when the permanent wilting-percentage will be reached in soils in which permanently rooted crops are growing. To do this we first secure three to five points on the extraction-curve during the spring and project the line until it reaches a moisture-content corresponding to the permanent wilting-percentage. The corresponding date on the time-axis gives the approximate time when the readily available soil-moisture will be exhausted. The extrapolation of the moisture-extraction curve as a straight line is based on the assumption that the changes in evaporating conditions, during the period under consideration, are not great enough to cause the curve to depart from linearity. We have found the extraction-curves to be essentially straight lines. In this way we are able to determine the date when the first irrigation should be applied. By following the same procedure during the summer months we can find out when the other irrigations are necessary. Inasmuch as we have followed this plan in many places, we can predict with reasonable accuracy the safe interval between irrigations on a number of different types of soil.

Mature orchards in the interior sections of California ordinarily exhaust the readily available moisture to a depth of six feet or more by about the first part of July. In irrigated regions the moisture-supply is replenished from time to time during the growing season, but in the unirrigated areas the trees are without readily available moisture after the moisture from the rains from the previous winter is exhausted. Similarly, there are large areas of forests, brush, or grasslands that are without available soil-moisture for considerable periods each year. Depending on the rainfall and the kind and depth of soil, all or part of the winter rainfall goes to increase the moisture-content from the permanent wilting-percentage to the moisture-equivalent. If the amount required to refill the soil-reservoir is known, that portion of the rainfall that is free to move over the surface or underground, and become available for use elsewhere, can be calculated. Inasmuch as the permanent wilting-percentage is a constant, the amount of water necessary to refill the soil-reservoir is the same whether the readily available moisture is exhausted in July or in October.

The equipment needed is relatively simple, does not get out of adjustment easily, and lasts a long time. The necessary items are a hammer, preferably weighing 25 or 30 pounds, a set of soil-tubes capable of withstanding hard use, an electric oven, a balance weighing to 0.1 gram, and a sufficient number of cans. The size of the cans will be determined by the procedure to be followed--small cans, if the samples are to be kept separate, and large ones if several cores are placed in each can. The cans should have tight-fitting covers and should preferably be lacquered

to prevent rusting. We use ointment-cans for the small samples and baking-powder cans for the composite samples. The cans are best transported in boxes with tight covers in which the cans rest snugly. The boxes should be constructed so that when the lid is put in place, there is no danger of the covers coming off the cans.

The success of soil-moisture studies with orchard trees and many other agricultural crops has often brought up the question, why cannot these methods be used for the study of the use of water by forest-trees and other native vegetation? Immediately, there come to mind the real or imaginary objections to trying to secure soil-moisture records from forest and brush-covered areas. The chief difficulty seems to be in securing plots where the soil is deep enough and uniform enough so that the resulting soil-moisture record may be interpreted with a fair degree of accuracy. However, there are areas where it would be feasible to secure samples, as for example, in many places in the Aiken soil-series, where the soil is deep and fairly free from rock. We have taken samples in orchards at elevations up to 3,200 feet.

The results obtained by the Range-Management Committee of the California Agricultural Experiment Station illustrate what may be accomplished even under adverse conditions. During the rainfall-year, September 1940 to September 1941, soil-samples were taken at frequent intervals, in most cases weekly, in 12 pairs of plots in Shasta and Tehama counties in California. These plots were located in typical foothill-grazing areas covered with brush and some trees. The purpose of the work was to obtain records of the changes of soil-moisture in covered and denuded areas, and to measure the losses of moisture from the soil under these two conditions. Most of the plots have rough, broken topography, and there was a large amount of gravel in the soil. Two pairs of these plots were on the Corning and Redding Soil Series, developed on old valley-fill material, containing gravel which varied from small-sized particles up to large cobblestones. At first it was thought that the only way soil-samples could be obtained under these conditions would be to dig trenches and to take samples from the faces of them. This proved impractical because of the frequency of sampling desired. After trying various means of soil-sampling, it was found that the soil-tube could be used even under these adverse conditions. In fact it proved to be the only practical means. Excellent records of the moisture-changes were obtained, and the results indicate that soil-sampling by means of a tube would yield data from which the transpiration- and evaporation-losses could be determined.

Soil which contains gravel always presents a difficult question--whether to screen out the gravel or to base the determinations upon the whole sample. In the work mentioned, the samples were weighed and dried when they reached the laboratory. Determinations were calculated on the entire sample. Gravel, larger than two mm, was then screened from the sample and the moisture recalculated on the basis of the gravel-free soil. An analysis of the results showed that removal of the gravel by screening was unnecessary because when the results were plotted upon the basis of the entire sample, they were consistent enough to calculate the amount of water in the soil at various times.

Experiments on losses through transpiration are frequently measured over a short period and then calculated for the entire season. These experiments are generally planned in such a way that the plants are grown in containers that can be sealed against loss by evaporation or drainage, and the transpiration-losses found by weighing the containers at intervals. At the University of California we have grown plants in containers varying in size from those holding 600 grams up to those holding about 1,000 kg of soil. These experiments yielded excellent results as far as the determination of the moisture-equivalent and permanent wilting-percentages were concerned, but were of but little value in determining rates of transpiration. Many of these experiments were conducted under conditions where light, temperature, humidity, and length of day were all carefully controlled. Some of the other difficulties encountered are described in a recent paper [Plant Physiology, v. 16, pp. 821-826, 1941]. The danger of using quantitative values for transpiration from plants in containers for the estimation of transpiration from surrounding watershed-areas was pointed out by the Committee in 1941.

Other methods of determining the water evaporated from watershed-areas by calculation from the results obtained by the use of potometers, various devices for drawing measured quantities of air over leaf-surfaces, and the change of color of hygroscopic paper are not satisfactory. They give results of value in comparing one small plant with another, but are so difficult to manipulate and give such erratic readings that it would be unsafe to calculate the amounts of water used, say on an acre-basis. It would seem that in areas having a long dry season, and where results were to be interpreted on the basis of the yield of water from a given watershed, the rate of transpiration measured during a brief period would be of comparatively little value.

If the rainless season is long enough to exhaust the moisture-supply before the beginning of the next rainy season, the amount necessary to replace that lost by transpiration and evaporation would be the same each year whether the transpiration-rate was fast and all of the available moisture was used up early in the season, or whether it was so slow that the available supply was not used until several months later. It would seem that the end-point, or the permanent wilting-percentage, is of much more importance than the rate at which this condition was reached.

In many areas in the West, there is no replenishment of soil-moisture from the time rains cease in the spring until they begin again in the fall. The amount of water that can be used by vegetation is that between the moisture-equivalent and the permanent wilting-percentage, and conversely, this is the amount that must be replaced by rains each year in permeable soils before there is any addition to the water-yield of the area involved except in cases where rainfall-intensities exceed the rate in infiltration. In many cases the amount lost by transpiration and evaporation and, consequently, the amount required to refill the reservoir can be determined by two sets of soil-samples--one taken soon after the spring rains stop and the other taken just before the fall rains start. Of course, if there is rainfall during the summer, soil-samples would have to be taken often enough to measure the resulting fluctuations in soil-moisture.

The study of soil-moisture conditions in the field seems to be a method of direct approach to the problem of determining losses from a watershed that will give results that may be used with confidence.

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COMMENTS

N. W. CUMMINGS (San Bernardino Valley Junior College)--In making the extrapolation of the moisture-extraction curve which he describes, Dr. HENDRICKSON assumes that the time-rate of moisture-loss is constant over the interval involved. This is, of course, equivalent to saying that the time-rate of energy-supply is constant, and since solar radiation is the most important single component of energy, Dr. HENDRICKSON'S procedure is roughly equivalent to assuming that insolation is constant over the interval.

Although this assumption may render possible a computation which is better than no computation at all, it can very easily be improved. For example, a trigonometric variation instead of a constant would improve the prediction appreciably, but an actual measure of insolation would be better still. Although insolation-records may not be available at all desired points, they are not entirely lacking by any means. There is, for example, a good record at Riverside. The extrapolation would require, of course, a prediction of the insolation for the unexpired part of the season, but that could be based on the records of previous years.

S. T. HARDING (University of California)--Gravel, as the term is used in the foregoing paper, is the soil-man's gravel, not the engineer's. Many members of the Section of Hydrology are engineers using gravel as the coarser aggregate in concrete. The soil-man's gravel is the engineer's sand. Dr. HENDRICKSON has given the maximum size retained in the sample, but this additional comment may help to avoid confusion.

It may also be desirable to emphasize somewhat more that the recommended method of determining evaporation from a watershed would be applicable primarily to areas with negligible rainfall during the main growing-season. Sufficient sampling to give losses where frequent rains occur would result in amounts of work and cost that would be prohibitive except for small areas.

J. KITTREDGE (University of California)--In a heavy clay-loam of the Los Osos series near Berkeley, sampling for soil-moisture in trenched plots to determine evaporation from denuded and from shaded and litter-covered areas has involved certain difficulties. The volume-weights as determined with a tube when the soil-moisture is near field-capacity and again when it approaches the wilting-point are quite unreliable as compared with those at intermediate moisture-contents and with those determined by the paraffin-immersion method. In the one condition, the soil is plastic and sticky, in the other, hard and brittle. Cores six inches long give less erratic results than those two inches long.

The area is subject to frequent fogs during the summer and in sampling at intervals of three to six days, several records have indicated gains in moisture-content during rainless periods, presumably resulting from condensation or from movement of moisture in the vapor-phase from deeper moister layers.

By repeated sampling at short intervals, the computed depths of evaporation can be cumulated and plotted over time in days to give a curve which rises steeply at first while the soil is moist and at a decreasing rate as it dries until the trend approaches the horizontal as the moisture-content approaches the wilting-point. With such a curve or curves for different soil-types, and a daily record of precipitation, it might be possible to determine the total evaporation by summing the depths evaporated as read from the curve for the number of days between each two rains, and thus arriving at a total seasonal evaporation even in a locality of frequent rains.

H. G. WILM (Rocky Mountain Forest and Range Experiment Station)--In a study recently started near Fraser, Colorado, the object is to determine the influence of timber-cutting on autumn soil-moisture deficiencies. Of course the treatment showing the least deficiencies should be optimum for water-yield, since snow-melt would have to replenish less soil-storage before adding to ground-water and to stream-flow.

For the first year's samples, ten sampling spots were taken at random in each of the 20 "unimproved" half-plots, so that there are 40 sites in each major treatment. One set of moisture-samples was taken in September, each representing the average of soil-depths from 2 to 18 inches below the duff-layer. Eighteen inches is the average depth to parent material, and should include practically all of the pine-root systems. A small post-hole digger was used for obtaining the samples. Another set will be taken in the spring, just after the last snow has left the ground, to provide an estimate of field-capacity. In addition, moisture-equivalents will be determined for each sample (both autumn and spring) to determine the relation of field-capacity to moisture-equivalent for these soils. If the correlation is good enough in later years the trouble may be saved of taking spring moisture-measurements, using the moisture-equivalent of autumn samples instead. The measured spring soil-moisture should very closely approximate field-capacity; this idea is well supported by Dr. HENDRICKSON'S manuscript and a recent paper by G. M. BROWNING [Soil Sci., pp. 445-450, December, 1941].

The study will be continued for probably four years, and repeated after about a decade to determine the effect of reproduction and other components of the developing understory. Sampling sites will be randomized anew each autumn, so that at the end of four years 200 spots will have been sampled under each major treatment.

In analysis, the dependent variable will be soil-moisture deficiency per sample or per plot, expressed as grams per hundred grams of oven-dry soil. Independent variables in covariance will be the content of gravel above two mm, total summer rainfall per plot, and the average distance from each sampling spot to surrounding or overhanging crowns. A preliminary analysis of the first year's data will evaluate the magnitude of sampling-errors, so that we shall know whether or not we need to increase the number of samples in each later year. Then the final analysis will be made of annual average soil-moisture deficiency per plot, as follows:

Source of variation	Degrees of freedom
Between means of	
(1) treatments	4
(2) blocks	3
(3) years	3
Interactions	
1 by 2	12[a]
1 by 3	12[a]
2 by 3	9
Triple	36[a]
Total (4 years' data, 20 plots)	79[a]

The reference "a" above indicates that in covariance one degree of freedom should be subtracted from each of these figures for each independent variable.

Either the "treatment-by-block" or the "treatment-by-season" interaction may be used as experimental error, whichever mean square is larger. As compared to Dr. HENDRICKSON'S procedure, we plan to use the whole sample including gravel, and to adjust each sample value by covariance to the average gravel-content of all samples. This procedure should remove the objections to using either the whole sample or a screened one. Introduction of the crown-distance concomitant should tend to remove much of the treatment-effect. It will be interesting to see how completely soil-moisture is associated with degree of canopy-opening.

Current developments during the year include several items of interest. Measurements of evaporation from snow are being continued each spring, with pans of different areas at the Rocky Mountain Forest and Range Experiment Station near Fraser, Colorado. In the 55-day period following March 20, 1941, the evaporation averaged a little less than 0.01 inch per day.

At the same station rainfall-interception by mature lodgepole-pine stands, in which different amounts of timber were reserved after cutting, showed net rainfall varying from 69.3 per cent of gross on the virgin plots to 95.4 per cent on the clear-cut areas, with the intermediate treatments approximating a straight line between the two extremes. The effects were found to be associated entirely with the size of openings in the canopy.

At the Manitou Experimental Forest net rainfall under young ponderosa pine averaged about 80 per cent of gross, with most of the loss accounted for by initial crown-storage. The difference in net rainfall between winter and summer interception was not significant.

A comment on the present situation and an interesting new prospect are contained in the following statement by Dr. CUMMINGS.

Until now, the evaporation-problem has presented a dilemma. If we attempt to proceed on strictly scientific grounds, without making any assumptions or approximations which require further work for their complete justification, we encounter expense which under many conditions is prohibitive for routine observations. On the other hand, if we resort to simplifying assumptions or approximations, the question of validity of the final result immediately enters. At this point we encounter a vicious cycle, because the question of validity can never be settled to the satisfaction of all concerned, unless a given set of assumptions is made, and the calculation made on that basis. The final result must then be compared with an actual change of lake-level or something corresponding to it in the case of vegetation or soil.

But the completion of all necessary steps involves some expense, even though the amount required may be far less than for a rigorous determination. This expense cannot be met without first establishing confidence in the usefulness of the outcome. Now, the establishing of this confidence is itself the objective of the comparison. We thus seem to have reached an impasse.

There appears to be no way of resolving the difficulty except by relating the evaporation-problem to some important industrial enterprise so as to provide an incentive for obtaining the data required in one or more of the various approximate solutions that have been proposed. This incentive could, of course, come out of the evaporation-problem itself, provided the need for reliable information was great enough. An example would be litigation, and there are some places where this may actually come about unless the matter is settled some other way at an earlier date.

It is, however, reasonable to hope that a more satisfactory solution may become possible on account of the following current development-work, which has for its object the measurement of solar and sky radiation as a basis for predicting the dissipation of fog. There seems to be considerable likelihood that photoelectric pyrheliometers will, within the next year or so, be established at a large number of points, and thus provide continuous records of insolation as measured by such instruments. If these can be satisfactorily correlated with other types of pyrheliometer (which seems likely) we shall have the data needed for the testing on a wide-spread scale, of the approximations in the application of the energy-equations.

The prospects for usefulness may be illustrated by a description of a combination of circumstances existing in Riverside County, California. Lake Elsinore is one of the very few bodies of water for which evaporation-determinations can be made by direct observation of lake-levels. A Weather Bureau pan is being operated near the lake. At the University of California at Riverside are a thermoelectric pyrheliometer, a sunshine-recorder, and a Weather Bureau evaporation-pan If, then, a photoelectric pyrheliometer is destined to be located at March Field, we shall be in a position to test a large number of correlations, some of which may be very important. Some of these tests, and perhaps others, not included in this group, will, if all goes well, become possible at other points.

During 1941 the Division of Irrigation, Soil Conservation Service, completed as a part of the Pecos River Joint Investigation, a report to the National Resources Planning Board on "Consumptive water use and requirements" by HARRY F. BLANEY, PAUL A. EWING, KARL V. MORIN, and WAYNE D. CRIDDLE. The report covers comprehensive studies made in 1940 by the Division of Irrigation on consumptive use of water by agricultural crops and native vegetation

in the Pecos River Valley areas. As a part of this investigation nine Class-A evaporation-stations, extending some 500 miles along the river in New Mexico and Texas, were established in cooperation with the Weather Bureau for the purpose of determining the relation of evaporation to evapo-transpiration in various sub-basins. In addition to the usual equipment each station included a water-tight tank containing soil in which was growing native vegetation. A key evapo-transpiration station, located at Carlsbad, New Mexico, included tanks for the measurement of water-consumption by tamarisk (salt-cedar), sacaton, saltgrass, and tules, as well as evaporation from bare soil and free-water surface. Consumptive use of water in several large irrigation-units was determined by the inflow-outflow and integration-methods. From long-period evaporation, humidity- and temperature-records and daytime hours, empirical formulas were developed for estimating evaporation from a free-water surface and consumptive use of water by native vegetation having access to an ample ground-water supply.

The general equation is $U = K C$ = annual use in inches, in which K = annual coefficient (varies with type of water-surface and vegetation), $C = 1.03\ T\ (114 - H)$ approximately for latitudes 30° north to 40° north = annual-use index, T = annual mean temperature in F°, and H = annual average relative humidity. Tentative values of K for evaporation for conditions on the Pecos River are K = 0.0164 for lake-surface and K = 0.0234 for Weather Bureau pan. In computing consumptive use, the annual use (U) is divided into two parts, namely, growing-season use ($u_g = k_g c_g$) and winter use ($u_w = k_w c_w$), thus $U = k_g c_g + k_w c_w$. The values of c_g and c_w are derived from monthly-use index (c) in which $c = t\ p\ (114 - h)$, t = mean monthly temperature, p = monthly per cent of annual daytime hours, and h = average monthly relative humidity.

REPORT OF SUB-COMMITTEE ON LAND FORMS OF THE COMMITTEE ON DYNAMICS OF STREAMS, 1941-42

Irving B. Crosby, Chairman of Sub-Committee

The Sub-Committee on Land Forms of the Committee on Dynamics of Streams of the American Geophysical Union has given special study to the causes and controlling factors of stream-meanders. Members of the Committee and their colleagues have supervised studies on this and related problems. Model studies of the meanders were made at the United States Waterways Experiment Station at Vicksburg, Mississippi, and GERARD H. MATTHES, a member of the Committee, reports that:

"Stream-meanders were made the subject of extended experimental study at the United States Waterways Experiment Station, Vicksburg, Mississippi, during the past year. Several different materials were tried out, but the principal experiments were conducted in a bed of pulverized coal 125 feet long by 40 feet wide. The objective has been to ascertain the relative importance of the various basic factors involved. By maintaining the coal-bed at a uniform gradient throughout and permitting the model-stream to select its own hydraulic gradients two of the five basic variables were maintained practically constant, namely, the valley-slope and the resistance of the materials composing bed and banks. [In this connection see GERARD H. MATTHES, Basic aspects of stream-meanders, Trans. Amer. Geophys. Union, Pt. III, pp. 632-636, 1941.] Variations in water-discharge and bed-load discharge were the principal variables experimented with. Toward the close of the season a new factor was introduced which hitherto has not received the recognition that appears due it, namely, vegetation. After unsuccessful attempts to simulate vegetation through artificial expedients, it was found possible to cause actual plants (Panicum clandestinum) to grow in the coal-bed, and provide a fair simulation of willows in the prototype. The results obtained indicate that dense vegetation, such as willows and cottonwoods, along the banks of a stream and particularly on convex bars, exerts a marked influence on bed-load movement during high stages by promoting the upward as well as riverward growth of convex bars, thereby increasing the caving of the concave banks opposite. At the time the tests were discontinued for the duration of the cold season, it had become apparent that in the case of alluvial streams carrying appreciable sediment-loads the vegetation as a factor affecting stream-bed morphology, is of much greater importance than is commonly attributed to it.

"Probably the most important contributions made during the season's operations, and also the most valuable from a practical engineering viewpoint, are the observations made of the manner and direction of movement of bed-load materials during (1) low stages, (2) initial rising stages, (3) medium rising stages, (4) high rising stages, (5) crest-stages, (6) high falling stages, (7) medium falling stages, and (8) low falling stages. These eight phases of a stream's flow-cycle are characterized distinctly by (a) sources of bed-load, (b) direction of travel, and (c) places of redeposition. Close observation has done much toward clarifying the cycle of bed-changes that take place in a stream free to meander, assuming no artificial restrictions. These

observations may be helpful in explaining the disagreement that has repeatedly cropped up as between observations by individuals confined to a single phase or to the two commonest phases, 'rising stages' and 'falling stages', without discriminating between the several portions of a rising stage or the several portions of a falling stage. Each portion has its distinct attributes.

"Experiments also were initiated having to do with practical problems as for instance the effect of various types of revetment, dredge-cuts across convex bars, and channel-dredging."

Mr. MATTHES in collaboration with Acting Director JOSEPH B. TIFFANY, JR., of the United States Waterways Experiment Station is preparing a paper describing the above tests, for publication at an early date.

During the year the Sub-Committee took up a new problem, the study of entrenched meanders in hard rocks. This involves different factors from those applying to meanders in unconsolidated sediments. This study has not yet progressed far enough to permit any conclusions. It is hoped to continue these investigations.

Boston, Massachusetts

NOTE

Urgent demands in connection with national-defense problems made necessary deferment of the preparation of reports for 1941-42 of the Research-Committees on (1) Physical Limnology, (2) Coordination of Hydrological Research between American Geophysical Union and American Society of Agricultural Engineers, (3) Flood-Waves, and (4) Dynamics of Streams. It is expected that these reports may be combined with those for the year 1942-43.

REMARKS ON HYDROLOGIC TERMINOLOGY

Robert E. Horton

When a science is advancing rapidly, as is hydrology today, especially when it is changing from an adolescent or qualitative to an adult or quantitative basis, new terms are needed in particular for the following two purposes: (1) To give expression to new ideas and concepts; (2) to give more definite, specific, quantitative meaning to terms and concepts heretofore chiefly qualitative. The terminology of a growing science is in some respects like the scaffolding of a building or like the false-work of an arch. If the building or arch is enlarged and the plans changed as the work proceeds, the scaffolding or false-work must also be adapted to the new conditions.

The selection of new terms to meet these new conditions in science is often rendered difficult by the fact that many of the best available terms are already preempted and in use--with meanings that are too general and indefinite.

The following principles are suggested for guidance in the selection of specific quantitative terms for use in hydrology or other sciences which are founded, as is hydrology, on physics:

(1) Where a term has an established meaning in the fundamental science in which it originated, and to which it primarily pertains, that meaning should not be changed or a new term substituted when it is applied in some other science.

(2) A term which has a specific meaning should not in general be replaced by a generic or less specific term.

The much overworked word "index" serves to illustrate this point. There are indexes of almost everything, from precocity to pregnancy. Each time the word "index" is used it is necessary to specifically define which and what index is referred to, and how it is determined. In most cases it is better, if possible, to specifically define the quantity and omit the term "index."

(3) In the adoption of new terms, due regard should be had to (a) the background of usage in the same connection, (b) the underlying physical principles involved in the process described, (c) the adequate, accurate, and apt description of what is intended, and the term should not do unnecessary violence to the English language.

It is unfortunate that in hydrology there have been various instances of attempts to introduce new terms without regard to the above principles, in particular without a sufficient knowledge of the background of the subject or the underlying physical principles. Under these conditions a new term may be introduced which amounts to little more than a confession of ignorance on the part of its sponsor.

A few examples will serve not only to illustrate the application of these principles but also the lack of their application in some instances, together with the difficulties which beset any one who attempts to improve existing terminology.

Frequency, recurrence-interval--The term "frequency" originated in and pertains primarily to statistical science. KURTZ and EDGERTON ["Statistical dictionary"] define the term "frequency" as "the number of observations or measures in one of the class-intervals of a frequency-distribution." There has been a tendency in hydrology to use the term "frequency" in the reciprocal sense of the average interval of recurrence of events in a given class. In accordance with the first principle above given, it seems that the term "frequency" should be retained with its original statistical meaning, and the term "recurrence-interval" should be used wherever the latter is referred to.

In this connection a situation exists which serves to illustrate the difficulty of finding adequately specific terms. In hydrology, recurrence-intervals of floods, either equalling or exceeding a given magnitude, are frequently used. For more frequent events there is no appreciable difference between the interval at which floods of a given magnitude will be either equalled or exceeded, and the interval at which the given flood-magnitude will be exceeded. In the case of major floods the difference does, however, become highly significant; and to avoid indefiniteness it seems desirable to limit the use of the words "recurrence-interval" to the average interval of occurrence of quantities (a) from and including a given magnitude to but not including the upper limit of the class interval, (b) including and exceeding a given limit. Where the average interval of floods exceeding a given limit but not including those of precisely that limit is under consideration, the expression "exceedance-interval" should be used.

Conversely, it is often desirable to use some expression to describe the average interval of occurrence of events having a magnitude less than a given quantity. The author has found no term more aptly descriptive of this meaning than the term "subceedance-interval."

Water-losses--The expression "water-losses" has a well-established meaning in English-speaking countries the world over to designate removal of water from a drainage-basin by evaporative processes, that is, interception, transpiration, and direct evaporation. To avoid the indefiniteness of the term "water-losses" it would perhaps be better to use the somewhat more cumbersome term "evaporative losses."

In recent years one finds the word "loss" used in hydrology to designate surface-runoff--this usage being common in connection with soil-conservation. Also a few persons have used the word "loss" to represent that part of the rain which does not produce runoff, including infiltration. It is true that from the viewpoint of agronomy, surface-runoff represents a deduction from water which would otherwise enter the soil; while from the viewpoint of the hydraulic engineer, interested in the quantity of water derived from runoff and available to fill reservoirs or supply water for power, irrigation, etc., infiltration is a deduction from immediate or surface-runoff. It is not, however, wholly or chiefly a deduction from total runoff, since infiltration supplies ground-water, which, in turn, commonly represents one-third to two-thirds of the total runoff of perennial streams. If both these quantities, that is, surface-runoff and infiltration plus interception, are called "losses," then since the sum of these quantities equals the rainfall, the absurd result follows that all rainfall is "loss."

Infiltration, infiltration-capacity, percolation--Infiltration is defined in the Oxford English Dictionary as the flow of a fluid into a substance through pores or small openings. It connotes flow into a substance in contradistinction to the word "percolation," which connotes flow through a porous substance. Infiltration connotes finely subdivided inflow in contradistinction to mass-inflow, such as occurs in ordinary hydraulic flow.

In spite of the accepted meaning of the term "infiltration," which precisely describes the manner of entrance of rainfall into the soil, other terms are sometimes used, such as "absorption," "intake," and "percolation." "Absorption" has quite a different meaning, and infiltration in general is not absorption in the accepted sense. It is a particular form of inflow.

The word "intake" has been used in a recent paper to include surface-detention, depression-storage, and infiltration. The authors of the paper state that "intake," so defined, is not infiltration, yet they frequently use the words "infiltration" and "intake" interchangeably. On the other hand, the "intake" as above defined can very readily be obtained from the results of an infiltrometer-experiment by merely subtracting the runoff-intensity from the rainfall-intensity, whereas the determination of the true infiltration-capacity during runoff is somewhat more laborious. It is probably for this reason that the term "intake" has sometimes been used. Actually if, as is often the case, it is assumed to be equivalent to infiltration-capacity during runoff, gross errors may result, since in reality the difference between rain-intensity and runoff-intensity represents the sum of the infiltration-capacity and the rate of accumulation of surface-detention. The latter rate may be, and frequently is, equivalent to 25 to 50 per cent of the infiltration-capacity in the earlier stages of runoff.

The author has defined infiltration-capacity [Trans. Amer. Geophys. Union, 1933, p. 447] as "the maximum rate at which a given soil can absorb rainfall when the soil is in a specified condition." There has been a tendency to substitute the words "infiltration-rate" or "infiltration-rates" for "infiltration-capacity," the reason given being that, to the minds of some, the word "capacity" connotes a volume, whereas infiltration-capacity is a rate. The word "capacity" is, however, commonly used with two different well-established meanings in the fundamental science of physics, namely, (1) to define a volume, (2) to define a maximum or limiting rate as, for example, the capacity of a pipe to carry a fluid under specified conditions, or the capacity of an electric conductor. These two meanings need never be confused. The term "infiltration-capacity" conforms to the second of these well-established usages. Substitution of the words "rate" or "rates" where capacity is intended leads to serious confusion in some cases, as it so happens that whenever rain-intensity is less than infiltration-capacity, infiltration takes place at a definite rate but not at the capacity-rate, whereas when rainfall-excess occurs, infiltration takes place at capacity-rate. Use of the single term "rate" indiscriminately in both cases leads to serious confusion and gross inaccuracy.

As to the word "percolation," not only does this word have an established usage different from "infiltration" or "infiltration-capacity," but its use to denote the latter has evidently arisen

from ignorance of the fact that when percolation occurs the soil is saturated, whereas when infiltration takes place, the soil is not fully saturated as a rule, but only saturated to or slightly above its field- or capillary-moisture-capacity. "Infiltration-capacity" and "percolation-capacity" or, as it is more commonly described in ground-water hydrology, "transmission-capacity," are related but they are not identical.

The compounding of confusion which may result by indefiniteness and lack of recognition of physical principles in such cases is illustrated by the following quotation given to the author and which purports to have been taken from a recently published paper:

> "The infiltration-rate is ordinarily at its maximum when water is first applied to the soil, and then as the pore-spaces become filled and wetting occurs, it decreases until a more or less stable minimum is reached. This minimum is the field percolation-rate, that is, the rate at which water moves through the saturated soil-profile, and it is governed largely by the permeability of the least pervious horizon. This minimum or stable infiltration-rate or percolation-rate, being a quantitative determination of the rapidity with which water can move through a saturated profile, is a measure of the internal drainage." (Underscored words are the author's.)

The author does not need to point out the inaccuracies in this statement.

The term "infiltration-index" has sometimes been used in place of "infiltration-capacity" on the ground that determinations of infiltration-capacity are always subject to some error. This is, however, also true of all measurements of quantities, direct or indirect. The substitution of the indefinite term "infiltration-index" for the specific, definite term "infiltration-capacity" on this ground is not justified and it is otherwise undesirable.

Detention, retention--The words "detention" and "retention" have been used in connection with the surface-phase of the hydrologic cycle with various meanings. The word "retention" seems objectionable as none of the rain falling on a drainage-basin is permanently retained. Either it is lost by evaporative processes or else it is temporarily detained by various forms of storage in its course through the hydrologic cycle. The author has defined "surface-detention" as "that part of the rain which remains on the ground-surface during rain and either runs off or is absorbed by infiltration after rain ends." While surface-runoff is taking place, it is water in transit as sheet-flow. The above definition is specific and less objectionable than the use of the term "retention" in a similar sense.

Subsurface and concealed-surface runoff--Cases arise where surface-runoff may take place in such a manner as not to be visible, as, for example, where it occurs through a layer of coarse material, sometimes through a thick matting of grass or mulch-cover; through a layer of plant-roots close to the soil-surface and under forest-litter; or even, in some cases, through a network of sun-cracks in the soil-surface. This has sometimes been called "subsurface-runoff," sometimes "ground-water flow." The term "subsurface-runoff" would not be objectionable were it not for the fact that it is likely to be confused with true ground-water flow. The term "ground-water flow" applied to this class of flow is highly objectionable on several counts; flow occurring close to the surface in the manner described has little in common with true ground-water flow. It is mostly turbulent flow, while true ground-water flow is mostly laminar. It persists only during rainfall-excess or for a short time thereafter, measured in hours or at the most in days, whereas ground-water flow persists on perennial streams at all times. Furthermore, surface-runoff follows the same laws and behaves in the same manner whether it actually occurs visibly on the ground surface, or is concealed and invisible, taking place just below the soil-surface where it is sustained by temporary detention below the soil-surface. Nevertheless, it may be desirable to distinguish between the two cases and, if so, flow which is essentially surface-runoff but which is concealed from view in some one of the ways described, may appropriately be called "concealed-surface runoff."

Channel-storage, valley-storage--The terms "channel-storage" and "valley-storage are both in use to describe water in transit in a system of stream-channels or within the channels and over adjacent flood-plains. The use of the term "channel-storage," where there is also flow outside the channels, is perhaps justified by the fact that when this occurs, the adjacent flood-plain becomes a part of the channel, in a hydraulic sense. The term "valley-storage" includes "channel-storage," whereas the term "channel-storage may or may not include flood-plain storage, dependent on the meaning assigned to the word "channel." In the great majority of stream-rises, channel-storage alone is present, using the word "channel" in a restricted sense. While the term "valley-storage" seems preferable in general, there seems to be no valid objection to the

use of the term "channel-storage" where the water in transit is definitely confined to the stream-channel exclusive of the flood-plain.

Darcy's or Poiseuille's law--The law expressing the relation of rate-of-flow to hydraulic gradient in cases of capillary or laminar flow is generally described in physics as "Poiseuille's law." The fact that this law also applies to ground-water flow was discovered by DARCY, who recognized and pointed out his indebtedness to POISEUILLE. In ground-water hydrology the same law is commonly referred to as "Darcy's law," apparently for no better reason than that some who use this law have found difficulty in either spelling or pronouncing POISEUILLE'S name. It is well established that credit for a general law or principle belongs to the man who developed it on a definite quantitative basis, as did POISEUILLE--not to one who subsequently applied the same law in some particular case.

Recharge--This term has been extensively used to describe replenishment of ground-water. Apparently borrowed from ballistics, the term "recharge" connotes complete replenishment by more or less definite quanta. That is not the manner in which ground-water storage is refilled. The restoration generally takes place by isolated quanta, varying, however, greatly in amount and duration. Furthermore, there may be, and frequently is, addition to the ground-water storage without bringing about an increase in the amount of storage above that existing when restoration began. This happens whenever the rate of accretion to an aquifer through infiltration is less than the rate of ground-water outflow. This condition is not reflected in the word "recharge," which certainly connotes an increase over the preexisting quantity. In view of these defects the author prefers the word "accretion," although there is much to support the earlier term "replenishment"--the principal objection to "replenishment" being that it is a more cumbersome word. It has, however, the background of usage by such distinguished pioneer hydrologists as Sir ALEXANDER BINNIE, CORNELIUS C. VERMEULE, and GEORGE W. RAFTER.

Plat, plot--The term "plot" has recently come into quite general use to specify a restricted parcel of ground on which, for example, a runoff-experiment is conducted. English usage, as may be seen from consulting, for example, the Oxford Dictionary, favors the word "plat" in this connection, a plat being a subdivision of the land-surface. No adequate justification for the use of the word "plot" has been offered.

In the preceding notes, references to persons and specific papers have been purposely omitted. The objective in this paper is to call attention to principles which may serve as guides in revision of hydrologic terminology and to give a few examples where standardization seems to be urgently needed. It seems necessary to state that these examples have not been chosen with reference to any particular person or paper but merely to bring to a focus the objections to certain terms and usages now more or less in vogue. The reader will undoubtedly notice various confessions of ignorance.

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DISCUSSION

O. E. MEINZER (U. S. Geological Survey, Washington, D. C.)--In regard to the important concept that is expressed by different authors by the terms loss, evaporative loss, evaporation, evaporation and transpiration, evapo-transpiration, consumptive use, or fly-off; I have never used the term fly-off but am wondering whether we might not do well to adopt that term for this concept. It is a short, simple term that would not be misunderstood and would be appropriate to designate the concept that is correlative to that expressed by the term runoff. (President GROVER pointed out that the term fly-off was suggested many years ago by W. J. McGEE.)

In regard to the different kinds of runoff, some of the authors of the forthcoming volume on Hydrology agreed to the use of the following terms: Surface-runoff and ground-water runoff, to make up total runoff; overland runoff, to designate the running surface-water before it reaches a stream-channel; and direct runoff, to designate the precipitated water that gets into the streams without retardation.

A STUDY OF VALLEY-STORAGE AND ITS EFFECT UPON THE FLOOD-HYDROGRAPH

H. K. Barrows

The object of this paper is the study of the effect of valley-storage upon the form of the flood-hydrograph and the relative amount of such storage available upon river-basins of different sizes and flow-characteristics.

Flood-hydrograph--On Figure 1 is shown a typical flood-hydrograph ABCD as observed September 20-26, 1938, in the so-called "hurricane-flood" of that year upon the Delaware River at

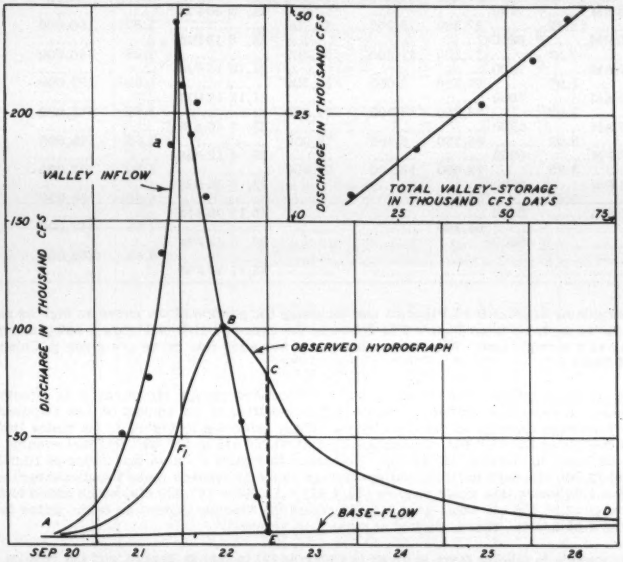

Fig. 1--Observed hydrograph, valley-inflow hydrograph, and valley-storage, Delaware River at Port Jervis, September, 1938

Port Jervis, New York, where the drainage-area is 3,076 square miles. The rising limb AB required about two days' time, during which flow increased to a maximum at B. The descending limb consists of the portion BC when the flow consisted in part of inflow to the river-basin and the remainder from valley-storage between the elevations corresponding to points B and C. At the point of inflection C inflow became zero and the remaining portion of the curve CD represents wholly valley-storage draining off from the river-basin. The approximate base flow is represented by the line AED.

Valley-storage--The conception of the portion CD of the descending limb of the flood-hydrograph as representing flow from valley-storage was suggested by ROBERT E. HORTON [see 1 of "References" at end of paper] and furnishes a ready and valuable means of studying this factor, which is of great effect upon the form of the flood-hydrograph.

It enables first [2] the determination of the amount of valley-storage as related to discharge, which can be conveniently accomplished by plotting a mass or total curve of valley-storage against

Table 1--Computations of valley-storage and inflow (based upon Fig. 1)

Flow, cfs	Descending limb						Rising limb			
	Day and time	Hours	Base-flow, cfs	Flow above base, cfs	Pondage, cfs-days, [(2)/24](5)	Σ pondage, cfs-days	Day and time	Hours	Valley-storage, cfs-days, [24/(8)]12000	(10) + (1
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	h m						h m			
10,000	27,12 00 M	.....	10,000	.....	.....	.....	21, 3 00 AM	.....	.....	.....
	.....	56.67	.....	6000	14,200	14,200	.....	7.60	37,000	55,000
20,000	25, 3 20 AM	.....	8000	.....	.....	.....	21,10 36 AM	.....	.....	.....
	.....	21.40	.....	17,250	15,300	29,500	.....	6.75	43,000	78,000
30,000	24, 5 55 AM	.....	7500	.....	.....	.....	21, 5 20 PM	.....	.....	.....
	.....	13.42	.....	27,250	15,200	44,700	.....	2.87	100,000	135,000
40,000	23, 4 30 PM	.....	8000	.....	.....	.....	21, 8 12 PM	.....	.....	.....
	.....	7.53	.....	37,250	11,600	56,300	.....	2.05	140,000	185,000
50,000	23, 9 08 AM	.....	7500	.....	.....	.....	21,10 15 PM	.....	.....	.....
	.....	3.97	.....	47,750	8,000	64,300	.....	1.55	187,000	242,000
60,000	23, 5 10 AM	.....	7000	.....	.....	.....	21,11 48 PM	.....	.....	.....
	.....	2.97	.....	58,250	7,300	71,600	.....	1.95	148,000	213,000
70,000	23, 2 15 AM	.....	6500	.....	.....	.....	22, 1 45 AM	.....	.....	.....
	.....	2.92	.....	68,750	8,300	79,900	.....	2.50	115,000	170,000
80,000	22,11 20 PM	.....	6000	.....	.....	.....	22, 4 15 AM	.....	.....	.....
	.....	3.93	.....	79,000	13,000	92,900	.....	2.35	122,000	207,000
90,000	22, 7 24 PM	.....	6000	.....	.....	.....	22, 6 36 AM	.....	.....	.....
	.....	6.40	.....	89,000	.....	.....	.....	4.40	66,000	161,000
101,000	22, 1 00 PM	.....	6000	.....	.....	.....	22,11 00 AM	.....	.....	.....
	.....	.....	.....	94,500	.....	.....	.....	7.75	-37,000	58,000
90,000	.....	.....	6000	.....	.....	.....	22, 6 45 PM	.....	.....	.....
	.....	.....	.....	.....	.....	.....	.....	4.60	-63,000	22,000
80,000	.....	.....	.....	.....	.....	.....	22,11 20 PM	.....	.....	.....

discharge beginning at point D on Figure 1 and including the portion of the curve as high as point C. Such a curve made up from Figure 1 is shown in the upper portion of Figure 1 and plots approximately as a straight line. The computations as a basis for this curve are given in Columns (1) to (7) of Table 1.

Valley- or basin-inflow--The rising limb of the flood-hydrograph shows runoff as affected by valley-storage. It represents valley- or basin-inflow modified by the amount of flow required to fill up valley-storage capacity as the river rises. Thus, referring to Figure 1, the rising limb reached 50,000 cfs at $10^h\ 15^m$ PM, September 21, and 60,000 cfs at $11^h\ 48^m$ PM that evening, a period of 1.55 hours to increase 10,000 cfs. Reference to Figure 1 shows that a rise of 10,000 cfs required 12,000 cfs-days to fill up valley-storage capacity between these two discharge-levels. In a period of 1.55 hours this would require (24/1.55) × 12,000 = 187,000 cfs, which added to the mean discharge of 55,000 cfs would give 242,000 cfs as the average valley- or basin-inflow for this period of 1.55 hours. This is plotted at point a on Figure 1.

This procedure in tabular form is given in Columns (8) to (11) in Table 1 and the results plotted upon Figure 1 result in the curve of valley- or basin-inflow AaFBE. The maximum point F corresponds to the time of ceasing of rainfall; at point B the curve coincides with the flood-hydrograph ABCD; between B and E the inflow-curve is below the curve ABCD, the area BCE consisting of flow out of valley-storage; the point E is under the inflection point C and CD represents flow wholly from valley-storage.

It is of interest to note the great effect of valley-storage in reducing the peak-flow. Thus, in Figure 1 inflow to the basin reached a peak of about 200,000 cfs, whereas the peak as affected by valley-storage was actually 101,000 cfs, only half as great.

It is to be noted that the area of valley-inflow AaFBEA equals the total runoff-area ABCDEA and total valley-storage is shown by the area $AaBF_1A$ as well as the area BCDEB. Thus the plotting of the valley-inflow curve can be checked.

Valley-storage studies--As a preliminary study of valley-storage and its effects for different rivers, a set of computations similar to those in Table 1 were made for a group of rivers in the Northeast and the essential results tabulated in Table 2. These were all based upon tabular flood-hydrographs for the flood of September 1938 as given in Water-Supply Paper 867, and in-

clude four stations in the Connecticut River Basin, three stations in the Merrimack Basin, three stations in the Delaware Basin, and three stations upon other rivers.

Valley-storage characteristics.--Reference to Table 2 enables the following tentative remarks and deductions:

Table 2--Summary of valley-storage studies

No.	Station	Drainage-area, sq mi	Total valley-storage				Total runoff, inches	Valley-storage per inch of runoff		Peak-flow cfs	Peak-flow without valley-storage, cfs	Ratio [(12)/(11)]
			Cfs-days	Cfs-days per sq mi	Acre-ft per sq mi	Inches depth		Inches	Acre-ft per sq mi			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
	Connecticut											
1	Montague	7858	360,000	45.8	91.6	1.70	3.24	0.52	28.2	193,000	845,000	4.40
2	Vernon	6240	204,000	32.6	65.2	1.31	2.08	0.63	31.4	132,500	525,000	3.96
3	White River Junction	4068	180,000	44.2	88.4	1.65	2.35	0.70	37.5	82,400	348,000	4.24
4	South Newbury	2825	90,000	32.0	64.0	1.20	1.70	0.71	37.7	42,000	154,000	3.64
	Merrimack											
5	Lowell	4635	134,000	29.0	58.0	1.08	2.75	0.39	21.0	120,000	192,000	1.60
6	Franklin	1000	46,000	46.0	92.0	1.70	4.10	0.41	22.5	54,400	82,000	1.50
7	Plymouth	622	36,000	58.0	116.0	2.20	4.70	0.47	24.7	50,900	98,000	1.92
	Delaware											
8	Riegelsville	6344	150,000	23.6	47.2	0.90	1.90	0.47	25.9	123,000	168,000	1.35
9	Belvidere	4542	136,000	29.8	59.6	1.12	2.04	0.55	27.2	116,000	245,000	2.12
10	Port Jervis	3076	126,000	41.0	82.0	1.54	2.14	0.72	38.4	100,000	243,000	2.43
	Winooski											
11	Essex Junction	1079	14,300	13.2	26.4	0.50	1.53	0.33	17.2	34,000	40,000	1.18
	Quinebaug											
12	Jewett City	711	29,000	40.6	81.2	1.30	3.28	0.40	24.8	23,000	41,000	1.78
	West											
13	Newfane	308	16,400	53.0	106.0	2.00	4.55	0.44	23.4	57,000	120,000	2.10
	Mean			37.6	75.2	1.40	2.89	0.50	26.9	86,785	238.539	2.48

Column (3)--A range of drainage-area from about 300 to 8,000 square miles is included.
Column (4)--Total valley-storage ranges from about 360,000 to 14,000 cfs-days.
Column (5)--Valley-storage per square mile varies from about 13 to 58 cfs-days, averaging 37.6 cfs-days.
Column (6)--Valley-storage in acre-feet per square mile.
Column (7)--Valley-storage in inches depth, ranging between 0.50 and 2.20 inches.
Column (8)--Total runoff above base-flow, ranging from about 4.7 to 1.5 inches.
Columns (9) and (10)--As valley-storage is directly related to total runoff, it is necessary for comparative purposes to determine the valley-storage per inch of total runoff. Columns (9) and (10) are perhaps the most significant columns in Table 2, as they enable the comparison of valley-storage amounts upon different rivers and points on the same river.

From Column (9) it will be seen that "Unit valley-storage" ranged from 0.33 to 0.72 inch depth, averaging 0.50 inch for all stations. Expressed in acre-feet per square mile of drainage-area [Column (10) this is from 17 to 38 and averages 27 acre-feet per square mile.

Table 2, Columns (9) and (10), shows that "Unit valley-storage" tends to increase as drainage-area decreases. In other words, valley-storage per square mile appears to be in general greater in the upper reaches of rivers than lower down. This interesting tentative conclusion should be confirmed by a wider range of studies.

Columns (11) to (13) show peak-flows as observed and as they would have been without valley-storage (in other words, valley-inflow) and their corresponding ratios. These ratios reach as high as 4.4 and show in a striking manner the great influence of valley-storage upon the form of the flood-hydrograph. This is also indicated by considering the average river in Table 2, with 0.50 inch of valley-storage per inch of runoff. For a great flood, of say six inches runoff, this means approximately $6.0 \times 0.5 = 3.0$ inches of valley-storage, which would greatly lessen the actual flood-peak as compared with that of valley-inflow.

Conclusion--The valley-inflow hydrograph should be of value in the study of infiltration, enabling as it does the construction of a mass-curve of valley-inflow for comparison with a mass-curve of precipitation.

It is clear that valley-storage is a most important natural agent in helping to smooth out flood-flows and of such importance as to warrant further and more detailed study.

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[1] Trans. Amer. Geophys. Union, 1936, Pt. II, p. 408.
[2] Turner and Burdoin, The flood hydrograph, J. Boston Soc. Civ. Eng., July 1941.

Boston, Massachusetts

DISCUSSION

WALDO E. SMITH (Soil Conservation Service, Washington, D. C.)--During the recession-phases of flood-flow, valley-storage on a given basin is confined between two surfaces converging going upstream, with the greatest separation at the outlet or gaging-station. During the rising stages, however, the valley-storage is of an entirely different form. It again is confined between two surfaces but they tend to diverge for a distance upstream, ultimately converging at the fringe of the watershed. Something less than the greatest distance between these surfaces frequently occurs at the lower end or the point of outflow. The distance between these two surfaces at the point of outflow is related by the rating-curve to the rate of flow. The author has in turn developed the relationship between the rate of outflow and the valley-storage under recession-conditions. This relationship developed from the recession-curve obviously cannot hold for the rising phase. This, I believe, is the chief shortcoming of the author's presentation. The author should acknowledge the extensive work done in the field of valley-storage and its great effect on flood-flow. In recent years, much attention has been given to this by numerous investigators in the United States Geological Survey [see 1 of "References" at end of discussion], the Army Engineers [2], the Tennessee Valley Authority [3], and elsewhere [4]. A year ago Dr. HORTON presented to this group his method for deriving what he defined as the "virtual channel-inflow graph" [5], in which he took into some account this difference in the storage-relation and attempted to construct his virtual-inflow graph on the basis of other known characteristics. His use of the word "virtual" was well advised inasmuch as this hydrograph represented inflow only in so far as it was indicated

by means of the relationship established between channel-storage and the discharge or gage-height on the gage downstream. If water in the channel-system does not affect the gage-height at the outlet as it should according to the storage-discharge relationship, then this will cause the virtual-inflow hydrograph to differ from the true-inflow hydrograph. The fact that water may occupy a position in the channel-system without being reflected on the outlet-gage is illustrated in Dr. HORTON'S paper [6] in the several virtual-inflow graphs that he determined for the outflow from Guernsey Reservoir in Wyoming and Nebraska. The water was released from the reservoir into the channel-system below the dam May 30. The water was in the channel-system for over two days, until June 2, before there was any observation of it through the discharge-storage relationship at Lisco and Oshkosh. It is thus reasonable to conclude that under natural conditions water may also exist in upstream and headwater positions in a channel-system under natural flood-conditions for some period, actually be a part of the channel- or valley-storage and long since have been channel-inflow before this appears on the virtual inflow-hydrograph. The proper discharge versus valley-storage relationship for the determination of the true channel-inflow hydrograph is not known and is indeterminate for the rising stage because for zero-discharge, storage may vary from zero to a maximum. We do, however, know that the storage on the rising stage is greatly different from the storage under recession-conditions. A comparison of the precipitation-excess graph with the virtual-inflow graph will give a measure of total water in transit in addition to that storage represented in the discharge-storage relationship. This probably includes all of the overland flow as well as the volume of water in the channels not yet reflected on the outlet-gage.

In Figure 1 the author showed the relation developed between Q and S by a straight line, the equation of which I have found to be $Q = 0.817S - 6200$. If the two subsequent points also had been plotted, the resulting line would have been substantially different. These both involved quantities that were still on the recession-side of the point of inflection. Later the author used the ratio 10/12 (instead of 0.817) as the ratio between the increase in flow and the increase in valley-storage. The plotting of the two additional points would have shown more definitely this curve to be concave upward. It approximates an exponential form of the order $Q = 0.0112S^{1.38}$. However, this holds for the recession-condition only. On the rising side, as indicated earlier, the storage for a given rate of flow is substantially higher, resulting in a valley-inflow hydrograph that rises more abruptly than the author shows. This has resulted in the deduction that "unit valley-storage tends to increase as the drainage-areas decreases," which I believe to be erroneous especially for the rising stages.

The author has indicated that the mass-curve of rainfall and the mass-curve of valley-inflow should be of value in the study of infiltration. I would like to turn this around and say that the mass-curve of precipitation-excess and the mass-curve of the true valley-inflow should be very valuable in a study of surface-detention, that is, water en route to the channels. It would be interesting to have shown the values of precipitation-excess on the hydrograph shown in Figure 1. Had all values been reduced to inches per hour and the necessary infiltration-studies undertaken, this would probably have been very revealing in showing the modification of the peak-rate of rainfall-excess by surface-detention, assuming the valley-storage curve to be the true one. The author has mentioned that the point F on Figure 1 represents the time of cessation of rainfall. This probably more nearly corresponds with (assuming the channel-inflow curve to be correct) the crest-flow from surface-detention and would normally follow the period of maximum precipitation-excess by a short time-lag.

Attention should be called to the fact that the values in Column (11), Table 1, are not instantaneous values as used by the author in Figure 1, but represent averages for the intervals shown in Column (9). As drawn, this is not serious except in the case of point F, which instead of being a peak-value is an average value for 1.55 hours.

It should be noted that many of the basic values in Table 2 differ substantially from data published in Water-Supply Paper 867 which the author cites. These differences are chiefly in Columns (8) and (11). For example, the author gives 3.60 inches as the amount of runoff from the Connecticut River at White River Junction for the hurricane-flood alone, whereas the Water-Supply Paper gives only 3.46 inches for the entire month of September. The author shows more square mile-inches of runoff for that station than the one at Vernon, at which point the drainage-area is over 50 per cent greater.

No mention is made of the substantial artificial storage in reservoirs on most of the streams listed in Table 2. It would be interesting to know how this storage was handled in relation to the valley-storage.

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[5] ROBERT E. HORTON, Virtual channel-inflow graphs, Trans. Amer. Geophys. Union, 1941, p. 811.

[6] ROBERT E. HORTON, Flood-crest reduction by channel-storage, Trans. Amer. Geophys. Union, 1941, p. 820.

H. K. BARROWS (Author's closure)--WALDO E. SMITH states: "The author has in turn developed the relationship between the rate of outflow and the valley-storage under recession-conditions. This relationship developed from the recession-curve obviously cannot hold for the rising phase. This, I believe, is the chief weakness of the author's presentation." The question is, as the author sees it, from a practical point of view what error is likely in using valley-storage as determined from the downward limb of the hydrograph and applying it to the curve for the uprising limb? While the method suggested is, of course, approximate, he believes that it may not be seriously in error and it certainly supports the general thesis of the great effect of valley-storage on the form of the flood-hydrograph.

Considering first the discharge-rating at the lower end of the river which was taken at Montague, for the reach above Montague there is certainly no great difference in slope for a given discharge at either rising or falling stage. If this were a serious matter, it would be necessary to take account of it in the data for the flood-hydrographs. The same thing is true for the other stations up the river, namely, Vernon, White River Junction, South Newbury, etc. These "samples" seem to indicate that the slopes on these reaches, particularly for higher stages, are not essentially different for a given elevation at the station-point, whether at rising or falling stage. It is fair to assume that many other reaches along the river would be in the same category. The author has a feeling, therefore, that while approximate, this method is perhaps not in serious error, except in special cases.

The author would prefer to call this method one of necessary approximation, rather than "a weakness in the presentation," as suggested by Mr. SMITH. The method is offered as an approximate practical solution of the effect of valley-storage on the flood-hydrograph which it is hoped may be useful. Mr. SMITH thinks that "the author should acknowledge the extensive work done in the field of valley-storage and its great effect on flood-flow." The author has certainly not in any way belittled such previous work, but there is hardly time in a ten-minute preliminary paper to review the whole field related to the paper. Obviously, too, there was not time to go into precipitation-excess and other matters which would be of interest.

The author welcomes constructive criticism and suggestions as to further study of the important factor of valley-storage.

STATISTICAL CONTROL-CURVES FOR FLOOD-DISCHARGES

E. J. Gumbel

For sufficiently large and accurate numbers of observations, the distribution of the flood-discharges, x, can be satisfactorily explained by the theory of largest values [see 4 of "References" at end of paper]. Until now we have determined the two constants which occur in this theory by the method of moments. This implies the calculation of the arithmetic mean and of the standard deviation. The purpose of this article is to simplify and, at the same time, improve the determination of the constants, to establish confidence limits for the flood-discharges, and to indicate several methods of comparison between theory and observation.

The probability $W^*(x)$ of a flood-discharge inferior to x is

$$W^*(x) = \exp\,[-\exp\,(-y)] \tag{1}$$

and the distribution $w^*(x)$ of the flood-discharges is

$$w^*(x) = \alpha \exp\,[-y - \exp\,(-y)] \tag{2}$$

where

$$y = \alpha\,(x - u) \tag{3}$$

is the reduced variable. The numerical values of the probability $w^*(x)$ as a function of y are given in Table 4, Column (2). The formulas contain two constants, u and $1/\alpha$ which have to be determined from the observations. In accordance with usual practice, we shall express them by a mean and a measure of dispersion.

The mean deviation--As the measure of dispersion we use the mean deviation θ which is defined as the mean of the absolute deviations of the observations x_m from the theoretical mean $\bar{x}$

$$\theta = 1/n \sum_{m=1}^{n} \left| x_m - \bar{x} \right| = 2/n \sum_{m=1}^{m'} (\bar{x} - x_m)$$

or

$$\theta = 2/n\,(m'\bar{x} - \sum_{m=1}^{m'} x_m)$$

Here $x_1, x_2, \ldots x_m, \ldots x_n$ are the annual flood-discharges arranged in increasing magnitude, n is the number of years, $\bar{x}$ is the theoretical mean annual flood, and finally m' is the serial number of the observed flood which is just below the mean flood. As the theoretical mean flood $\bar{x}$ is unknown, we use instead the observed mean annual flood $\bar{u}$ which leads to

$$\theta = 2/n\,(m'\bar{u} - \sum_{m=1}^{m'} x_m) \tag{4}$$

To account for the use of $\bar{u}$, we introduce a correction formula

$$\bar{\theta} = \theta \sqrt{n/(n-1)} \tag{5}$$

which is similar to the correction used for the calculation of the standard deviation (formula 3 of our previous paper [5]. In the sum contained in (4), each flood-discharge x_m has to be used as often as it occurred, but the calculation of the n absolute deviations between the observed floods and their mean is avoided.

We shall now show the relation between the mean deviation θ and the constant $1/\alpha$. For a continuous variable x having the mean $\bar{x}$ and the probability W(x) of a value equal to or less than x, the mean deviation is

$$\theta = 2 \int_{-\infty}^{\bar{x}} W(x)dx$$

In our case, the mean is $\bar{x} = C$, where $C = 0.57722$ is EULER'S constant, and we obtain from (1) and (3)

$$\theta = 2/\alpha \int_{-\infty}^{C} \exp [- \exp (-y)]dy$$

Introducing

$$\exp (-y) = z; \quad \exp (-C) = 0.56146$$

the mean error becomes the integral logarithm

$$\theta = -2/\alpha \int_{\infty}^{0.56146} \exp (-z)dz/z = 0.98299/\alpha$$

This numerical value was taken from the tables prepared by the Work Projects Administration [7]. Finally the constant $1/\alpha$ becomes a multiple of the mean deviation

$$1/\alpha = 1.01731\ \theta \tag{6}$$

For the numerical determination of $1/\alpha$ we use the corrected value $\bar{\theta}$ calculated from the observations.

The nature of the other constant u is evident. The distribution (2) has one and only one maximum at y = 0. From the transformation (3) it follows that u is the mode, that is, the most probable annual flood. This value differs from the mean annual flood $\bar{u}$ as the distribution (3) of floods is asymmetric. The probability of a flood to be equal to or less than the mode is, according to (1),

$$W^*(u) = 1/e \tag{7}$$

This equation can be used for a direct determination of the constant u. For n observations, u is the mth observation where $m = n\,W^*(x)$ is

$$m = 0.36788\ n \tag{8}$$

For 1,000 observations the mode lies between the 367th and 368th observation. But the relation (8) is only valid for large n's. The question arises what correction has to be introduced for small n's. To find the answer and for the construction of control-curves, we use the theory of the mth values.

The mth flood--We first consider an arbitrary distribution w(x) which will be replaced later by the distribution (2). For a distribution w(x) called initial, and for n observations, the mth value is such that m-1 values are below, and n-m values above it. Therefore, the distribution $v_m(x, n)$ of the mth value, where

$$v_m(x, n) = \binom{n}{m} m\ W^{m-1} (1 - W)^{n-m}\ w(x) \tag{9}$$

depends upon the initial distribution w(x). The most probable mth value obtained by differentiating (9) is the solution of

$$(m - 1)w/W - (n - m)w/(1 - W) = - w'/w$$

or

$$m - nW = 1 - W - [(w'/w)\ (W/w)]\ (1 - W) \tag{10}$$

For increasing numbers of observations the expression on the left side becomes large compared to the right side, provided the derivative remains finite. Therefore, the most probable mth value $\tilde{x}_m$ converges towards the solution of

$$W(\tilde{x}_m) = m/n \tag{11}$$

as is to be expected from equation (8).

For the determination of the constant u from the mode we consider the solution of (10) for small values of n. The problem is to calculate nW as a function of m. But instead of a most probable mth value, we want to determine from the observations a value having a given probability which need not be an mth value and which in our case is given by (7). We choose a general relation between m and λ

$$m = \lambda\ (n + 1) \tag{12}$$

This formula attributes an mth value to a given probability λ. To see the meaning of (12) we consider as example the median, where the probability is $\lambda = 1/2$. The median is an mth value such that $(n - 1)/2$ observations lie above and also below it. Therefore, $m = (n + 1)/2$ which is a special case of (12). For an arbitrary mth value, equation (10) becomes by virtue of (12)

$$\lambda\ (n + 1) = W\ (n + 1) + 1 - 2W - [(w'/w)\ (W/w)](1 - W) \tag{13}$$

Instead of W and w, we introduce the probability (1) and the distribution (2) respectively. Then

$$- [(w'/w)\ (W/w)] = (1 - e^{-y})e^{y} = e^{y} - 1 = 1/\log_e\ (1/W^*) - 1$$

and W^*, as a function of λ, becomes according to (13)

$$n W^* = n\lambda - [n/(n + 1)]\ \Delta \tag{14}$$

This equation takes the place of (11) for small values of n. The most probable serial number, $\tilde{m} = n W^*$, is in first approximation equal to n times the probability λ. Besides there is a correction Δ independent of n, where

$$\Delta = - W^* + (1 - W^*)/\log_e\ (1/W^*) \tag{15}$$

The term Δ is a function of W^*. For increasing numbers of n, the third member in (14) diminishes rapidly compared to the two other members. Therefore, it is legitimate to put $W^* = \lambda$ within the term Δ and to neglect the second correction which ought to be made. The expression Δ becomes then a numerical value which depends only on the given probability λ.

The most probable flood--Equations (14) and (15) can be used for the numerical determination of the constant u, the most probable annual flood, from a table containing the floods arranged in increasing magnitude. For the mode we obtain from (7) the correction $\Delta = 1 - 2/e$. For n observations the mode is therefore the $\tilde{m}$th value where

$$\tilde{m} = 0.36788\ n - 0.26424\ n/(n + 1) \tag{16}$$

For increasing values of n this expression converges of course towards the prior solution (8). Figure 1 shows how the quotient $\tilde{m}/n$ converges towards 1/e.

Table 1, Column (3), gives the serial number $\tilde{m}$ of the mode as a function of the number of ob-

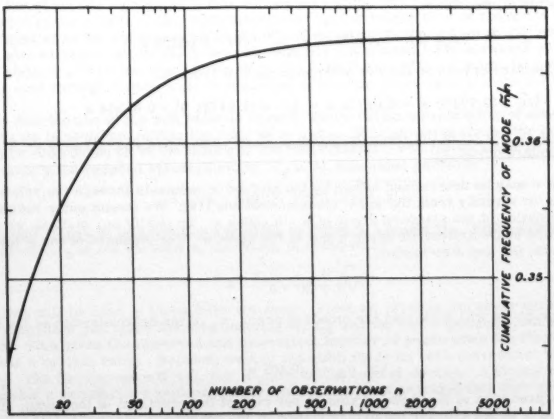

Fig. 1--Corrected probability of the most probable annual flood

Table 1--Serial number of most probable annual flood

n (1)	$\tilde{m}/n$ (2)	$\tilde{m}$ (3)
10	.343857	3.4386
15	.351364	5.2705
20	.355297	7.1059
25	.357716	8.9429
30	.359355	10.7807
35	.360539	12.6189
40	.361435	14.4574
50	.362698	18.1349
60	.363547	21.8129
70	.364158	25.4910
80	.364617	29.1694
90	.364976	32.8478
100	.365263	36.5263

servations n [Column (1)]. The second column, containing the cumulative frequency $\tilde{m}/n$, is used for interpolation of values n which are not contained in the Table. For a given number of observations we take from Table 1 the serial number of the mode. The corresponding mth flood gives the constant u. By this method we can determine the constant u directly from the observations.

Comparison with the method of moments--The determination of the constants through (6) and (16) consists in the calculation of the mean deviation which leads to $1/\alpha$. The other constant u is found by interpolation between two observed values. Evidently this procedure is much simpler than the previous determination from the arithmetic mean and the standard deviation. The obvious question arises whether we do not lose some information contained in our material. Any determination of constants from a sample does not lead to fixed numerical values. The parameters we calculate are new statistical variables which have a certain variance. The problem is whether the new determination of the constants is, for the distribution (2), as precise as the method of moments. This classical question is solved by the calculation of the standard errors involved. The larger the standard error, the less precise is the determination. For the normal distribution, for example, the calculation of the mean is more precise than the determination of the median, and the standard deviation is to be preferred to the mean deviation. However, this does not hold for all distributions. The precisions of the different means and measures of dispersion differ for specific distributions. This result has been emphasized by R. A. FISHER [1].

The constant $1/\alpha$ may be determined by the method of moments as $1/\alpha = 0.77970\ s$, where s is the standard deviation, or, by our method, as $1/\alpha = 1.01731\ \theta$. For any distribution, the standard error $\sigma(s)$ of the standard deviation s is for large values of n

$$\sqrt{n}\,\sigma(s) = s/2\,\sqrt{\beta_2 - 1}$$

where β_2 is the kurtosis used by SLADE [2]. The standard error $\sigma(\theta)$ of the mean deviation θ is, for any distribution and for large values of n

$$\sqrt{n}\ \sigma(\theta) = \sqrt{s^2 - \theta^2}$$

For the distribution (2) we obtain

$$\sqrt{n}\ \sigma(s) = 1.04881\ s > \sqrt{n}\ \sigma(\theta) = 0.64232\ s$$

Therefore, the standard errors of the two determinations of $1/\alpha$ are

$$\sqrt{n}\ \sigma(0.77970\ s) = 0.81776\ s > \sqrt{n}\ \sigma(1.01731\ \theta) = 0.65344\ s$$

The determination of $1/\alpha$ from the mean deviation is 25 per cent more precise than its determination from the standard deviation.

The constant u may be determined either by the method of moments through the relation $u = \bar{u} - 0.45005\ s$, or directly from the mode through equation (16). We cannot enter here into the complicated calculation of the standard error of $\bar{u} - 0.45005\ s$. To justify our method, we compare the standard errors of the arithmetic mean $\bar{u}$ and of the mode u. The standard error $\sigma(\bar{u})$ of the arithmetic mean is, for any distribution,

$$\sqrt{n}\ \sigma(\bar{u}) = s$$

In the next paragraph we will show that the standard error σ_u of the determination of the mode u from (16) is

$$\sqrt{n}\ \sigma_u = 1.02205\ s$$

Consequently the precision of the mode attains 98 per cent of the precision of the mean. Therefore, it is legitimate to use (16) for the determination of the constant u, the mode, interpreted as an mth value.

Our method seems to contradict the general opinion according to which the determination of the mode from the observations is very unreliable. But this holds only for the usual method which is based on the classified observations, whereas we determine the mode from the unclassified observations according to the theory.

The method of moments conserves the arithmetic mean and the standard deviation (moment of inertia) whereas the present method conserves the mode and the mean deviation. From the graphical point of view, the conservation of the most probable value has an aesthetic advantage. The new method for the determination of the two constants is evidently simpler and besides more precise in the statistical sense. But we use only two observations for the determination of the constant u. Therefore, the observations must be sufficiently precise in the technical sense.

Control-curves for the comparison of theory and observation--We consider now the asymptotic properties of the distribution (9) of the mth values. It has been shown [3] that, for large numbers of observations n and for m of the order n/2, this distribution converges generally towards a normal distribution. This is a generalization of the well-known theorem concerning the distribution of the median. For large n's the expectation of the mth value is given by (11), and the standard error σ_x of the mth value is

$$\sigma_x \sqrt{n} = \sqrt{W(x)\,[(1 - W(x)]}/w(x) \qquad (17)$$

If we apply this formula to the distribution of the largest values, we have to replace w(x) and W(x) by w*(x) and W*(x). The standard errors of the median and of the mode (interpreted as an mth value) are special cases of (17). If we determine the mode from (16), we may attribute to it the standard error σ_u obtained from (17) by introducing (7). This leads to

$$\sigma_u \sqrt{n} = [1/w^*(u)]\,\sqrt{(1/e)\,[1 - (1/e)]}$$

From (2) we obtain

$$\sigma_u \sqrt{n} = (1/\alpha)\,\sqrt{e - 1}$$

Instead of $(1/\alpha)$ we use the standard error s which is related to $(1/\alpha)$ by $(1/\alpha) = 0.77970\ s$ and reach

$$\sigma_u \sqrt{n} = 1.02205\ s \qquad (17')$$

This is the formula we used in the preceding paragraph. Formula (17) does not contain the number m. Therefore, a standard error σ_x might be attributed to any value of the variable. This holds for all x's for which the probabilities are neither very small nor very large. The standard error can be applied to the middle of the distribution, that is, for values of m of the order n/2. It can neither be applied to the beginning nor to the end of the distribution, as we would have to deal, in that case, with extreme values which are not normally distributed. The standard error of the mth value is a statistical function which depends on the distribution w(x). It might be a monotonic function or pass through a maximum or minimum according to the nature of the initial distribution.

As the distribution of the mth value is normal, there exists a probability of about 2/3 that an observed value is contained within the interval $x \mp \sigma_x$. This property allows the construction of curves which control the fit of the theory to the observations. For the distribution (2) and the reduced variable y the reduced standard error σ_y of an mth value becomes

$$\sigma_y \sqrt{n} = \exp(y)\,\sqrt{\exp[\exp(-y)] - 1} \qquad (18)$$

The numerical values of this function are given in Table 4, Column (4). For a given stream the standard error σ_x of the variable x, the flood, is obtained by

$$\sigma_x = (\sqrt{n}\ \sigma_y)/(\sqrt{n}\,\alpha) \qquad (19)$$

This function will be used in three different ways. First we arrange the observations x_m in increasing magnitude and trace the step-function m, x_m and the corresponding theoretical frequency n W*(x), x. This gives the observed and theoretical number of years when the flood was equal to or less than a certain value. Besides, we add and subtract from each theoretical value its standard error σ_x. The two curves n W*(x), $x \mp \sigma_x$ are called control-curves. A theory may be considered as giving a satisfactory explanation for the observations provided that they are contained within this area.

Table 2--Observed flood-discharges and return-periods for Mississippi River

Serial number, m	Keokuk (Iowa)		Vicksburg (Mississippi)		Serial number, m	Keokuk (Iowa)		Vicksburg (Mississippi)	
	Flood-discharges, x_m	Return-period, $'T(x_m)$	Flood-discharges, x_m	Return-period, $'T(x_m)$		Flood-discharges, x_m	Return-period, $'T(x_m)$	Flood-discharges, x_m	Return-period, $'T(x_m)$
(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)
1	59.2	1.02	760	1.02	31	163	2.03	1406	2.63
2	84.2	1.03	866	1.04	32	169	2.10	1410	2.78
3	85	1.05	870	1.06	33	171	2.18	1410	2.94
4	105	1.07	912	1.09	34	175	2.26	1426	3.13
5	106	1.09	923	1.11	35	178	2.35	1453	3.33
6	108	1.11	945	1.14	36	178	2.44	1475	3.57
7	108	1.13	990	1.16	37	178	2.54	1480	3.85
8	110	1.15	994	1.19	38	181	2.65	1516	4.17
9	112	1.18	1018	1.22	39	181	2.77	1516	4.55
10	122	1.20	1021	1.25	40	190	2.90	1536	5.00
11	124	1.22	1043	1.28	41	192	3.05	1578	5.56
12	138	1.25	1057	1.32	42	192	3.21	1681	6.25
13	138	1.28	1060	1.35	43	201	3.39	1712	7.14
14	141	1.30	1073	1.39	44	203	3.59	1813	8.33
15	142	1.33	1185	1.43	45	205	3.81	1822	10.00
16	147	1.36	1190	1.47	46	212	4.07	1893	12.50
17	148	1.39	1194	1.52	47	212	4.36	1893	16.67
18	148	1.42	1212	1.56	48	213	4.69	2040	25.00
19	150	1.45	1230	1.61	49	220	5.08	2056	50.00
20	150	1.49	1260	1.67	50	230	5.55	2334	.....
21	150	1.53	1285	1.72	51	230	6.10	....	.....
22	150	1.56	1305	1.79	52	230	6.77	....	.....
23	156	1.61	1332	1.85	53	236	7.63	....	.....
24	156	1.65	1342	1.92	54	240	8.71	....	.....
25	158	1.69	1353	2.00	55	247	10.17	....	.....
26	159	1.74	1357	2.08	56	270	12.20	....	.....
27	160	1.79	1357	2.17	57	271	15.25	....	.....
28	160	1.85	1397	2.27	58	293	20.33	....	.....
29	161	1.91	1397	2.38	59	306	30.5	....	.....
30	163	1.97	1402	2.50	60	314	61	....	.....
					61	360	.....	....	.....

The same method may be applied to the return-period T as a function of the variable x. We plot the observed exceedence and recurrence-intervals $'T(x_m)$ and $''T(x_m)$ as functions of x_m, where

$$'T(x_m) = n/(n - m) \qquad ''T(x_m) = n/(n - m + 1) \tag{20}$$

The recurrence-intervals are obtained by attributing $'T(x_m)$ to x_{m+1}. To avoid the calculation of logarithms, we use semi-logarithmic paper. The observed curves are identical for small numbers m. We compare them to the theoretical return-periods T as functions of x, which are

$$T(x) = 1/[1 - W^*(x)] \tag{21}$$

These values are given in Table 4, Column (3). Besides, we trace the two values $x \mp \sigma_x$ as functions of T and reach control-curves.

Finally this method may be applied to the equiprobability-test. This comparison between theory and observation is based on the linear transformation (3). We take the observed values x_m having a frequency $W^*(x_m) = 0.05, 0.10, \ldots 0.95$. The corresponding theoretical values y, having the same probability obtained from (1), are

$$y = -\log_e [+\log_e (1/W^*)] \tag{22}$$

[Table 5, Column (2)]. According to (3), the values x_m, y ought to be situated on a straight line. In reality they will be scattered around it. By adding to, and subtracting from, the theoretical values x, given by the straight line, the standard errors σ_x, we obtain control-curves y, $x \mp \sigma_x$. The equiprobability-test has the advantage that no determination of the constants is needed.

Therefore, the procedure is very quick. But of course it is not based on all observations. For the construction of control-curves for this test we need the numerical values of the constants.

Finally we compare the observed and the theoretical distributions. The observed distribution consists of the numbers of observations contained within certain equidistant values of the variable. The length of these intervals and the starting point of the division are arbitrary. Too small a division leads to great variations of the contents of the different classes. Too broad a division effaces the characteristic shape of the curve. We shall use an appropriate multiple of the constant $1/\alpha$ as the length of the intervals. Besides we use the starting point x_0 (the initial flood) in such a way that the mode obtained from the classified observations differs only slightly from the mode obtained from the theory. In other words, the two arbitrary factors involved in this presentation of the observations are chosen according to the theory. The theoretical distribution (2) is of course the derivative of the probability (1). But for simplicity's sake we use instead the finite differences of $n\,W^*(x)$ corresponding to the divisions used for the observations. The comparison of the observed with the theoretical distribution is a more severe criterion than the other methods. Those are based on the cumulative probability whereas we use here its differential quotients. Therefore, the fit cannot be expected to be as good as for the other three methods.

The Mississippi River--As numerical examples for the methods explained above we choose the flood-discharges for the Mississippi River at Keokuk (Iowa) for the n = 61 years 1851, 1878-1937, and at Vicksburg (Mississippi) for the n = 50 years 1890-1939. Table 2 contains [Columns (2) and (4)] the observed flood-discharges arranged in increasing magnitudes and measured in 1,000 cubic

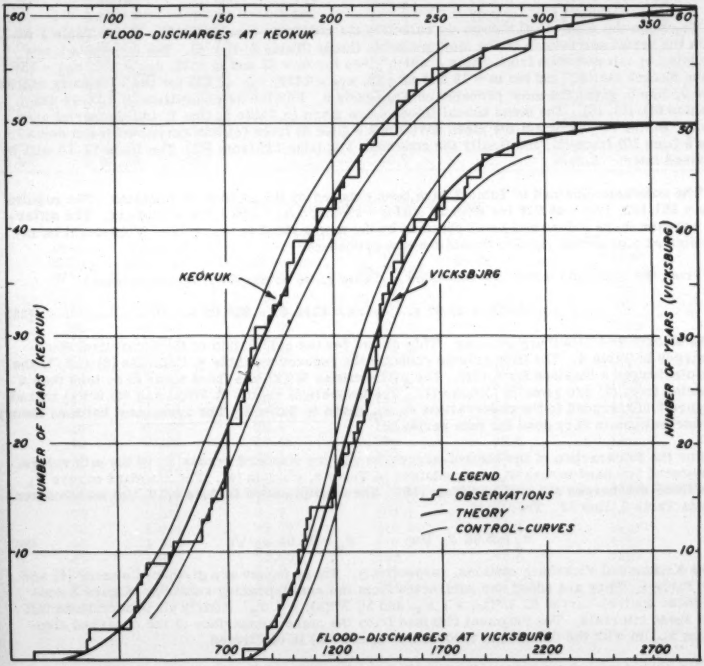

Fig. 2--Observed and theoretical frequency of the flood-discharges, Mississippi River

Table 3--Calculation of constants for Mississippi River

(1) Station	Keokuk (Iowa)	Vicksburg (Mississippi)
(2) Years	1851, 1878-1937	1890-1939
(3) Number of observations, n	61	50
(4) Serial number of mode, $\tilde{m}$	22.180	18.135
(5) Most probable flood, u	151.08	1214.43
(6) Sum of discharges, $\sum_1^n x_m$	10839.4	67780
(7) Mean flood, $\bar{u}$	177.695	1355.6
(8) Serial number, m'	34	25
(9) Mean deviation, θ	44.7616	258.8
(10) Corrected mean deviation, $\bar{\theta}$	45.1331	261.4275
(11) Constant, $1/\alpha$	45.9144	265.9528
(12) Factor in (19), $1/(\alpha\sqrt{n})$	5.88	37.61
(13) Reduced initial value, y_0	-2.25	-2.25
(14) Initial flood, x_0	47.8	616
(15) Reduced length of classes, Δ_y	0.75	1
(16) Length of classes, Δ_x	34.441	265.95

feet per second. Column (1) gives the serial number m. The observed values m, x_m are traced for both stations in Figure 2. Columns (3) and (5), which contain the observed recurrence-intervals, will be used later.

To obtain the theoretical curves we calculate the constants (see Table 3). From Table 1 we obtain the serial numbers $\tilde{m}$ of the most probable floods (Table 3, line 4). The constants u are calculated by interpolation from Table 2 which gives for m = 22 and m = 23, $x_{22} = 150$, $x_{23} = 156$ for the Keokuk station, and for m = 18 and m = 19, $x_{18} = 1212$, $x_{19} = 1230$ for the Vicksburg station. Table 3, line 5, gives the most probable annual floods u. For the determination of $1/\alpha$ we use formulas (4), (5), (6). The mean annual floods $\bar{u}$ are given in Table 3, line 7, and the serial numbers m' in line 8. We obtain the mean deviations θ (line 9) from (4), the corrected mean deviations $\bar{\theta}$ (line 10) from (5), and finally the constants $1/\alpha$ (line 11) from (6). The lines 12-16 will be explained later.

The constants obtained in Table 3 have been checked by the method of moments. The results are u = 151.192, $1/\alpha$ = 45.916 for Keokuk, and u = 1201.9, $1/\alpha$ = 266.1 for Vicksburg. The difference between these values and those obtained by the new method is negligible. This might be interpreted as a practical justification of the new procedure.

From the constants u and $1/\alpha$ contained in Table 3, we obtain the transformations

$$x = 151.08 + 45.91\ y \qquad x = 1214.43 + 265.95\ y \qquad (23)$$

for the Keokuk and Vicksburg stations. This allows for the calculation of the theoretical flood-discharges in Table 4. The first column contains the reduced variable y, Columns (5) and (7) the flood-discharges x obtained from (23). The probabilities W*(x) of a flood equal to or less than x calculated from (1) are given in Column (2). The theoretical values 61 W*(x) and 50 W*(x) traced in Figure 2 correspond to the observations m, x_m given in Table 2. The agreement between theory and observations is very good for both series.

For the construction of the control-curves we use the standard errors σ_x of the mth values. The reduced standard errors σ_y are contained in Table 4, Column (4). The standard errors σ_x of the flood-discharges are obtained from (19). The multiplicative factors $1/(\sigma\sqrt{n})$ involved are given in Table 3, line 12. Therefore,

$$\sigma_x = 5.88\ \sigma_y\sqrt{n} \qquad \sigma_x = 37.61\ \sigma_y\sqrt{n} \qquad (24)$$

for the Keokuk and Vicksburg stations, respectively. These values are given in Columns (6) and (8) of Table 4. They are added and subtracted from the corresponding values x. Figure 2 contains these control-curves 61 W*(x), $x \mp \sigma_x$, and 50 W*(x), $x \mp \sigma_x$. Nearly all observations fall within these intervals. The judgment obtained from the mere comparison of the observed step-function x_m, m with the theoretical frequencies x, n W*(x) is confirmed.

Our second way of comparison deals with the return-periods. The observed exceedence-intervals 'T(x_m) are given in Table 2, Columns (3) and (5), and are plotted on Figure 3, together

Table 4--Probabilities, return-periods, and control-curves

Reduced variable, y	Probability, W*(x)	Return-period, T(x)	Reduced standard error, σ_y	Keokuk		Vicksburg	
				Flood-discharge, x	Standard error, σ_x	Flood-discharge, x	Standard error, σ_x
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
-2.00	0.00062	1.00	.....	59.2	....	682.5	.....
-1.75	0.00317	1.00	.....	70.7	....	749.0	.....
-1.50	0.01131	1.01	.....	82.2	....	815.5	.....
-1.25	0.03049	1.03	.....	93.7	....	882.0	.....
-1.00	0.06599	1.07	1.384	105.2	8.1	948.5	52.1
-0.75	0.12039	1.14	1.277	116.6	7.5	1015.0	48.0
-0.50	0.19230	1.24	1.243	128.1	7.3	1081.5	46.8
-0.25	0.27693	1.38	1.258	139.6	7.4	1147.9	47.3
0.00	0.36788	1.58	1.310	151.1	7.7	1214.4	49.3
0.25	0.45896	1.85	1.393	162.6	8.2	1280.9	52.4
0.50	0.54524	2.20	1.505	174.0	8.9	1347.4	56.6
0.75	0.62352	2.66	1.645	185.5	9.7	1413.9	61.9
1.00	0.69220	3.25	1.812	197.0	10.7	1480.4	68.2
1.25	0.75088	4.01	2.010	208.5	11.8	1546.9	75.6
1.50	0.80001	5.00	2.241	220.0	13.2	1613.4	84.3
1.75	0.84048	6.27	2.507	231.4	14.7	1679.8	94.3
2.00	0.87342	7.90	2.813	242.9	16.5	1746.3	105.8
2.25	0.89996	10.00	3.163	254.4	18.6	1812.8	119.0
2.50	0.92119	12.69	3.564	265.9	20.9	1879.3	134.0
2.75	0.93807	16.15	4.018	277.4	23.6	1945.8	151.1
3.00	0.95143	20.59	.....	288.8	....	2012.3	.....
3.25	0.96197	26.30	.....	300.3	....	2078.8	.....
3.50	0.97025	33.61	.....	311.8	....	2145.3	.....
3.75	0.97675	43.01	.....	323.3	....	2211.8	.....
4.00	0.98185	55.10	.....	334.8	....	2278.2	.....
4.25	0.98584	70.62	.....	346.2	....	2344.7	.....
4.50	0.98895	90.56	.....	357.7	....	2411.2	.....
4.75	0.99138	116	.....	369.2	....	2477.7	.....
5.00	0.99329	149	.....	380.7	....	2544.2	.....

Table 5--The equi-probability test

Probability, W*(x)	Reduced variable, y	Keokuk		Vicksburg	
		Serial number, m = 61 W*(x)	Flood-discharge, x_m	Serial number, m = 50 W*(x)	Flood-discharge, x_m
(1)	(2)	(3)	(4)	(5)	(6)
.05	-1.097	3.05	86	2.5	868
.10	-0.834	6.1	108	5	923
.15	-0.640	9.15	112.5	7.5	992
.20	-0.476	12.2	138	10	1021
.25	-0.327	15.25	143.3	12.5	1059
.30	-0.186	18.3	148.6	15	1185
.35	-0.049	21.35	150	17.5	1203
.40	0.090	24.4	156.8	20	1260
.45	0.225	27.45	160	22.5	1319
.50	0.367	30.5	163	25	1353
.55	0.514	33.55	173.2	27.5	1377
.60	0.672	36.6	178	30	1402
.65	0.842	39.65	186.9	32.5	1410
.70	1.031	42.7	198.3	35	1453
.75	1.246	45.75	210.3	37.5	1498
.80	1.500	48.8	218.6	40	1536
.85	1.817	51.85	230	42.5	1697
.90	2.250	54.9	246.3	45	1822
.95	2.970	57.95	292.9	47.5	1967

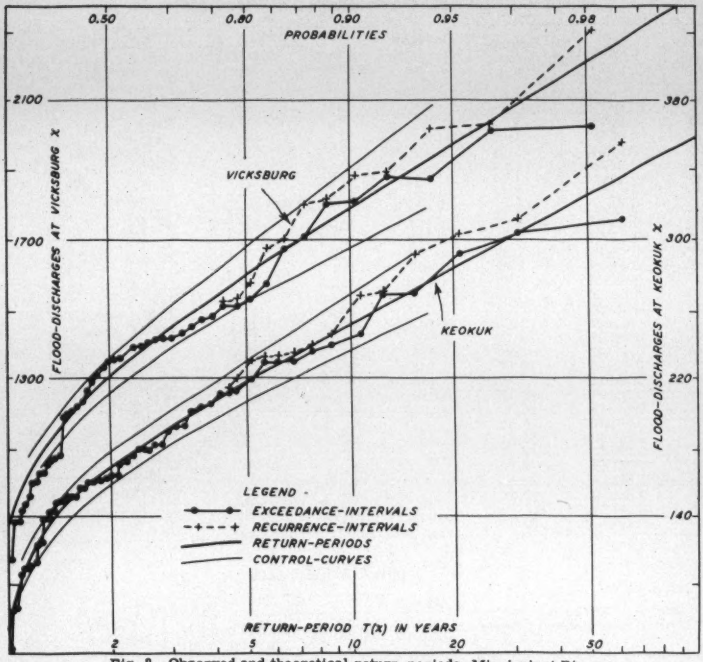

Fig. 3--Observed and theoretical return-periods, Mississippi River

with the observed recurrence-intervals. The corresponding theoretical flood-discharges [Table 4, Columns (5) and (7)] as functions of the return-periods [Table 4, Column (3)] are plotted on the same Figure. For small numbers m the theoretical values are almost identical with the observations. For large values of m the theoretical curves are contained between the two observed curves. To control the comparison between the observed recurrence- and exceedence-intervals and the theoretical return-periods, we attribute to the return-periods T(x) also the two values $x \mp \sigma_x$. Figure 3 shows that the observations are contained within these control-curves.

For the equiprobability-test we use the reduced variable y [Table 5, Column (2)] as a function of the probability W*(x) [Column (1)]. The corresponding serial numbers m = 61 W*(x) and m = 50 W*(x) are given in Columns (3) and (5). From Table 2 we obtain the corresponding flood-discharges [Table 5, Columns (4) and (6)]. The observed values x_m, y are traced in Figure 4 together with the theoretical straight line (23). Besides, we attribute to each mth flood-discharge x_m its standard deviation σ_x as taken from Table 4, Columns (6) and (8). The fit between theory and observations is very satisfactory.

Finally, Figures 5 and 6 contain the observed and theoretical distributions. The initial flood x_0 (the starting point of the division) and the lengths of the classes Δx which we have chosen are given at the end of Table 3 (lines 13-16). The observed distributions are obtained from Table 2 by enumerating the numbers of floods contained in the classes $x_0 + K\,\Delta x$ till $x_0 + (K + 1)\,\Delta x$, where K = 0, 1, 2 .....

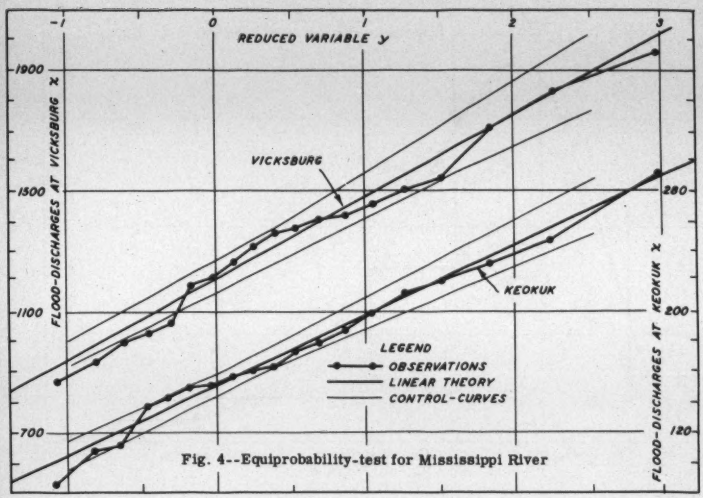

Fig. 4--Equiprobability-test for Mississippi River

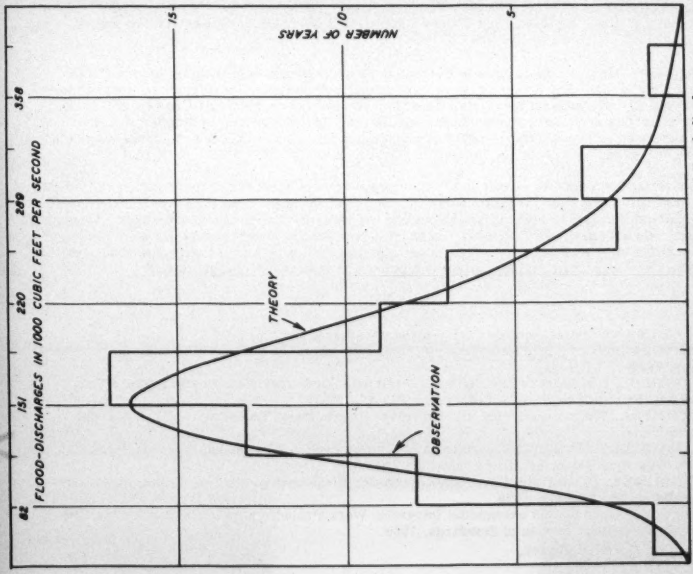

Fig. 5--Observed and theoretical distribution of flood-discharges, Mississippi River at Keokuk

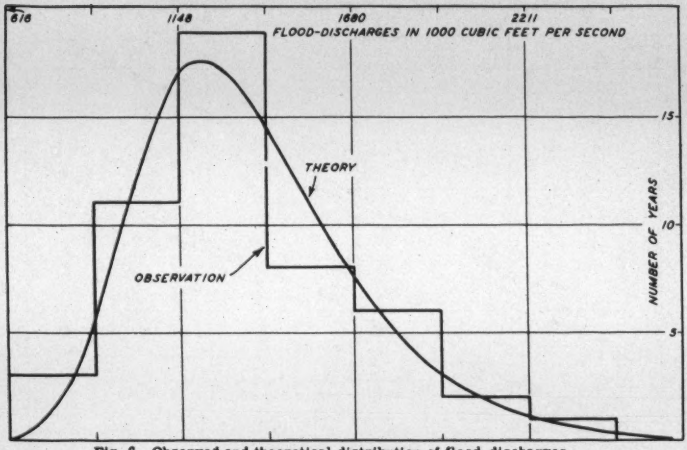

Fig. 6--Observed and theoretical distribution of flood-discharges, Mississippi River at Vicksburg

The theoretical distributions obtained from Table 4, Column (2), consist of the corresponding successive differences $61\,W^*(y + 0.75) - 61\,W^*(y)$ for the Keokuk and $50\,W^*(y + 1) - 50\,W^*(y)$ for the Vicksburg station. Figures 5 and 6 show a satisfactory agreement between theory and observations.

Conclusion--Many attempts have been made to find a mathematical formula for the flood-flows (see [2] and [6]). But the different authors introduced interpolation-formulas, whereas we claim the validity of a general theory, the theory of largest values which attributes a clear meaning to the constants and allows a systematic calculation. This procedure is simpler than the methods proposed until now, where higher moments and complicated functions of those moments have to be calculated.

The comparison used here leads to the conclusion that the theory of largest values reproduces the observed flood-flows for the Mississippi in a satisfactory way. If we take into account that, in previous publications [4] and [5], we have obtained the same result for the Rhine, Rhone, Tennessee, Connecticut, Cumberland, and Columbia rivers, it seems safe to conclude that our method is appropriate for obtaining a forecast for the frequency and magnitudes of future floods--provided that the observations are long and reliable, and that no important systematic change occurs.

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DISCUSSION

BRADFORD F. KIMBALL (New York Public Service Commission, Port Washington, New York)--Prof. GUMBEL'S recent papers applying the theoretical probability-distribution of maximum values of FISHER and TIPPETT to the problem of determining the return-periods of floods constitute a very important step forward in handling this problem. The technique for fitting is simple enough to appeal to engineers.

In the present paper GUMBEL brings out that for this type of probability-distribution computation of the modal value and the mean deviation of the observed annual floods subject the derived critical constants to smaller sampling errors than is the case when the mean value and the standard deviation are used as a basis for the computation. This simplifies the work as squares of deviations need not be computed.

Some will notice a gap in the reasoning where the relation

$$m = \lambda (n + 1)$$

is introduced. The reason for bringing in λ is that the preceding differential equation is based upon a set of integers m and n. Hence one must be able to pass from a given probability λ which is not in general associated with an integral number of observations, to the corresponding number m of a sample of n observations such that λ represents the probability that m - 1 observations have measures that are less than the measure x corresponding to the mth observation, and n - m observations have measures that are greater than this value x. Attention is called to the fact that the relation $m = \lambda (n + 1)$ holds correctly for the median value, for which λ must have the assigned value 1/2. However, there is more to this assumption than appears on the surface. The rule used by HAZEN was that the observed probability corresponding to a flood of serial number m was half way between m/n and (m - 1)/n. This is the same as taking $m - 1/2 = \lambda n$. This procedure also gives the right answer when applied to the median. Prof. GUMBEL has found objection to the use of the constant 1/2 and has informed the writer that in previous theoretical studies he has found that the relation $m = \lambda (n + 1)$ is to be preferred. This would mean that to determine a flood not to be exceeded in the next thousand years the chart should be read at $\lambda = 1000/1001$ rather than at $\lambda = 9995/1000$, or at 0.9990 rather than at 0.9995. This is a provocative result and the writer has been given to understand that Prof. GUMBEL is working on an article to clarify this matter.

The chief criticism that the present writer has of Prof. GUMBEL'S work is that the question of using a limited primary probability-distribution of stream-flows (not annual maxima) involving an upper limit dependent upon character of watershed has been omitted as if it were inconsequential. The writer believes that the use of an upper limit in the primary probability-distribution is called for in any complete theoretical consideration of the maxima of stream-flows or rainfall, since in extrapolation for purposes of forecasting frequency of extreme flows, such a consideration may have considerable numerical significance. This criticism will be considered in detail by the present writer in a paper to be submitted for publication at a later date [see Abstract, Annals Math. Statistics, v. 13, No. 1, p. 112, March, 1942].

GUMBEL'S "control-curves" indicate expected sampling variations from theoretical law. The fact that there is fairly good agreement between observation and theory in this respect is not proof that the assumed theoretical law could not be improved upon. Deviation between theory and observation is particularly apparent for the larger floods.

The use of an upper limit in the type of probability-distribution assumed for the stream-flow (not the annual maxima), gives a theoretical distribution of maximum floods which turns down at the right-hand end. Referring to GUMBEL'S paper of 1941 [E. J. GUMBEL, Probability-interpretation of the observed return-periods of floods, Trans. Amer. Geophys. Union, 1941, pp. 836-850], it is to be noted that in the charts for the Mississippi and Rhone rivers there is a decided tendency for the curves of observed return-periods to curve downward at the right-hand end, away from the theoretical curve. Some slight tendency to turn downwards is also noted in the charts for the Tennessee, Connecticut, and Columbia rivers. The only exception is that of the Rhine River. In this case the unusual character of the curve of observed return-periods would seem to indicate the desirability of obtaining further information about the manner in which the observations were made, or concerning the nature of the watershed involved. A watershed including all-year-round, snow-covered mountains might be the disturbing element here.

The use of the limited type of "primary" probability-distribution of stream-flows (not floods) does not preclude the use of a technique very similar to that proposed by Prof. GUMBEL in

setting up the FISHER-TIPPETT distribution of maximum flood-flows.

Hence the writer believes that the most important contribution in Prof. GUMBEL'S papers lies in his having brought out the logic in passing from the assumed probability-distribution, which applies to every-day stream-flow, to the probability-distribution of the FISHER-TIPPETT type, which applies to the annual maxima, and in calling attention to the inherent simplicity of the numerical computations needed in this transition.

With short records it is undoubtedly safer to assume the possibility of an unlimited stream-flow and use GUMBEL'S technique as presented. However, where records are of some length, the writer believes that a more accurate forecast of return-periods may be obtained by taking into account the existence of an upper limit of stream-flow.

R. S. GOODRIDGE (Soil Conservation Service, Washington, D. C.)--The Section of Hydrology is fortunate in having as able a mathematical scientist as Professor E. J. GUMBEL as a contributor to the Transactions of this Assembly.

The problem presented to hydrologists in the analysis of a series of flood-discharges requires, preferably, a statistical method providing the following desirable features:

(1) A method of curve-fitting which is free from individual bias--that is, a method by which two individuals working independently will produce identical curves.
(2) A curve which will reach the upper-limit values of flood-runoffs indicated by an analysis of similar records from a homogeneous region of common hydro-metrological characteristics.
(3) Provision for a distribution of the flood-events within the period of years of record.
(4) Satisfying the conditions imposed by the calculus of probabilities.
(5) Readily adaptable to field-use.

It is obvious that the theory of the largest values of a statistical variable is an appropriate tool for use in examining flood-arrays. Professor GUMBEL'S method provides the desired requisites, (1) to (5) above. He applies a distribution containing only two constants which materially simplifies the mechanical work involved. These constants are α and u.

Limitations and assumptions--Certain simplifying assumptions limit the use of the method generally except for the specific case set forth by the author. It is well that these be understood. Points in question follow:

(a) Use is made of the maximum mean daily flow of each year.
(b) Use of (a) precludes an application of the method except for large drainage-areas for which the mean daily flow is practically equal to the flood-peak discharge.
(c) Since long records are very few, it is desirable that the method be supplemented by procedures which will permit of an interpretation of a short record in terms of the longer records of the region--both of flood-runoffs as well as of precipitation.
(d) The use of the method may be extended by recognizing that the hydrologist is called upon to correlate the magnitudes of the floods in terms of their average recurrence-intervals with the damages resulting therefrom; therefore, an array of flood-events must be reviewed for the damage caused. The events causing similar damage should then be segregated on the basis of a basic stage of discharge.

In comment on points (a) and (b) above, the tolerances allowed in the concept of the mean daily flow of the maximum day occurring at equal time-intervals may be as easily made for the peak-discharges, provided the maximum of the year is used. It does not appear that the theory will fit values selected on the basis of the basic stage. Professor GUMBEL says that a method can be developed for use of a basic stage for out-of-bank flows which cause specific types of damage. The use of crest or flood-peak discharges will permit of the application of the method to small watersheds.

In regard to (c), the interpretation of short records, use may be made of the long records of the region both in precipitation and runoff. Correlations may be made with the precipitation-history in terms of the degree or strength of the fluctuations of excess or deficiency of precipitation. The series of flood-events for partial record-periods, when arrayed in terms of the average recurrence-intervals and the exceedance-intervals as Professor GUMBEL has done, lie in fitted curves some ordinal magnitude from the curve fitted to the composite record. These magnitudes may be associated with the degree of excess or deficiency of precipitation for corresponding periods. An adjustment for the period of record may then be empirically indicated.

In illustration of the foregoing principles, Figure A, showing the curves for partial record-periods of the Mississippi River at Le Claire, Iowa, and also the curves for the like series for the basin at Keokuk, Iowa, plotted by the California method with graphically fitted curves, extrapolated through use of the functional index to be discussed later, and Figure B, showing the precipitation-history of the region or basin in terms of the cumulative departure from the 90-year average (1850-1939), are used. It will be noted that the magnitudes of the flows of the river which may be

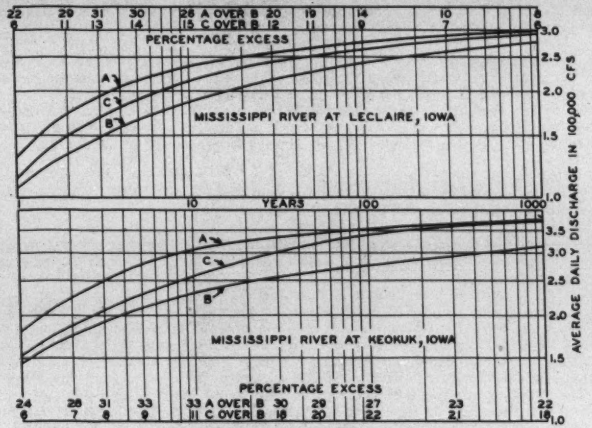


Fig. A--Average recurrence-intervals of flood-discharges, Mississippi River: Curve A during 1861-94 (34 years) at Le Claire (Iowa) and 1851, 1878-94 (44, 17 years) at Keokuk (Iowa); curve B during 1895-1939 (45 years) at Le Claire and 1895-1937 (43 years) at Keokuk; curve C during 1861-1939 (79 years) at Le Claire and 1851, 1878-1937 (87, 60 years) at at Keokuk

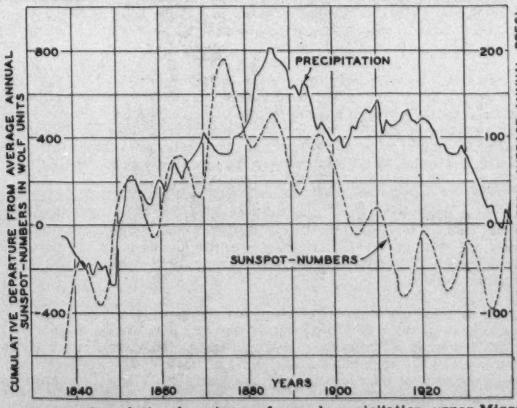

PRECIPITATION
SUNSPOT-NUMBERS
YEARS
CUMULATIVE DEPARTURE FROM AVERAGE ANNUAL SUNSPOT-NUMBERS IN WOLF UNITS
CUMULATIVE DEPARTURE FROM AVERAGE ANNUAL PRECIPITATION IN PER CENT

Fig. B--Cumulative departures of annual precipitation, upper Mississippi River above Le Claire (Iowa), and of sunspot-numbers, calculated from average for 90-year period, 1850-1939

expected on the average once in ten years on the A-curves exceed those on the B-curves by about 30 per cent. The percentages by which both the A-curve and the C, or the composite curve, exceed the B-curve are shown on the top and the bottom of the graphs. The A-curve was obtained from a plotting of the series of flood-events of record previous to 1895. The period of record of both gages is shown on the bottom of the graph. The B-curve is the plot of the series of record subsequent to 1894. The composite exceeds the B by 16 and 11 per cent at the ten-year interval, respectively. These percentages are significant, especially so when cognizance is taken of the percentages shown on the abscissa where the 30-year intervals of the B-curves are shown to approximate ten-year intervals on the C-curves.

Flood-damages are capitalized in terms of the expected average recurrence-intervals; accordingly, the monetary significance of the above at three per cent compounded annually in terms of the present value of $1, is that the 30-year event requires an investment of 41 cents as against 74 cents for the ten-year event, an increase of 80 per cent. It is obvious that such magnitudes resulting from the interpretation of a series of record-events has economic import. The 16 and 11 per cent ordinal values are projected to 80 per cent by the reduction in the average recurrence-interval values.

Only by means of a study of the characteristics of long records of a region can the approach to an evaluation of a shorter record be made.

It is the purpose of this discussion to bring attention to the degree of difference which may exist within a long record when portions of such a record conform to lengths of the records of other streams of the region.

Figures C and D are included to give the results of exploratory studies of the precipitation-history in other regions. The fluctuations of the departures of annual precipitation in the Youghiogheny River Watershed are illustrative of those of the basins of the Middle East. The Susquehanna River basin-indices, not included, fluctuate about the average even more, indicating the dampening influence of possibly two dominant moisture-sources, as from the Atlantic Gulf-stream or the Tropical Atlantic and the Tropical Gulf, to use the classification of Professor WILLETT. It will be noted that the trends of the departures of the Coosa River Watershed indices are opposed to those of the Mississippi River above Le Claire, Iowa. The Coosa River is the only one studied thus far which shows that uniformly. The one most similar is that for the point-record of San Diego shown on Figure D. The 20-year period of 1880-1900 in the San Diego pattern is consistent with the normal North American pattern, however. The only other opposed patterns which the writer has seen published are those for New England and England developed from the Hartford (Connecticut) precipitation-records and records of Wales (England) by CALEB MILLS SAVILLE. These appeared in "Some rainfall variations"[Quart. J. R. Met. Soc., 1934, p. 319]. The period studied there was from about 1866 to 1932, approximately 66 years instead of the 90 years which have been the bases of studies reported herein.

One may be concerned with the reference to the departure-sequence of the relative sunspot-numbers. This is used merely as a background reference, being the only continuous long-term record of insolation-activity, which is considered the initiating factor to make moisture available for precipitation. As a line of reference it serves to assist in estimating the degree of geographical phase-change which exists between regions. It is not offered to imply the existence of cyclic fluctuations. We are interested in the record only and any tendency to similarity is considered coincidental.

With respect to the point-record for Los Angeles shown on Figure D it must be stated that use was made of the indices developed by H. B. LYNCH for the Metropolitan Water District of Southern California in 1931. The precipitation-record for Los Angeles begins with the year 1872. The LYNCH indices were adjusted in terms of the average for the period 1850-1939 and incorporated with the actual record.

The last important point is that of a "ceiling" for the upper-limit values, or a reasonable limit for the flood-discharge which the hydrologist may estimate for the region of the watershed. Professor GUMBEL'S method will reach that ceiling through the extrapolation of the record-data. Several other methods will fail to reach such a "ceiling" through the limitation of the asymptote approached from an analysis of the record-data, which may be a "short" record developed by a relatively "dry" record-period.

Two valuable approaches for this "ceiling" are the hydro-meteorological estimates of the "maximum" storm of the region and the estimate of the flood-discharge which may be expected

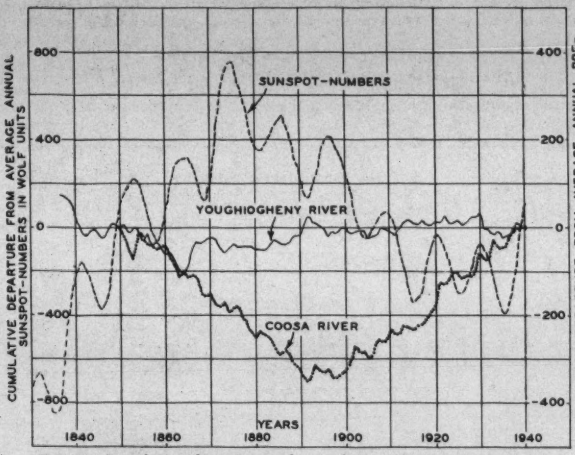


Fig. C--Cumulative departures of annual precipitation for the Coosa River (Georgia) and Youghiogheny River (Pennsylvania) watersheds, and of sunspot-numbers, calculated from average for 90-year period, 1850-1939

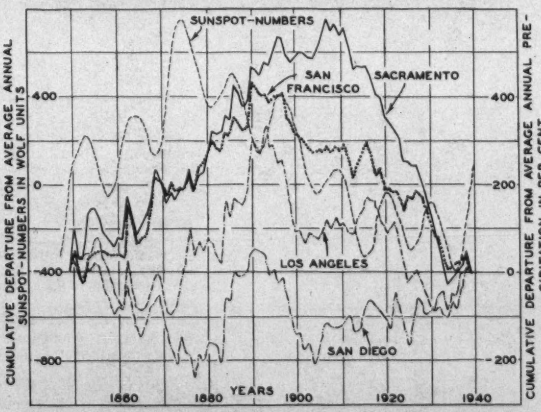


Fig. D--Cumulative departures of seasonal precipitation, California Region (point records only), and of sunspot-numbers, calculated from average for 90-year period, 1850-1939

from that storm and the use of a "functional-flood index" of the region of the watershed which is developed from the flood-discharge records of the region itself.

The "functional-flood index" is an index on the scale of 100 which will accommodate the flood-crest-area relationship indicated from a plot of the maximum flood-crest discharges of the

world. The flood-crest-area relationship so determined for areas, on log-log scales, of 0.1 to 2,000,000 square miles, may be expressed in two simplifying equations as follows:

$$\text{Areas less than 400 square miles, } Q = 10{,}000\ M^{0.707}$$

$$\text{Areas greater than 400 square miles, } Q = 230{,}000\ M^{0.184}$$

where Q = flood-crest discharge in cubic feet per second and M = drainage-area in square miles.

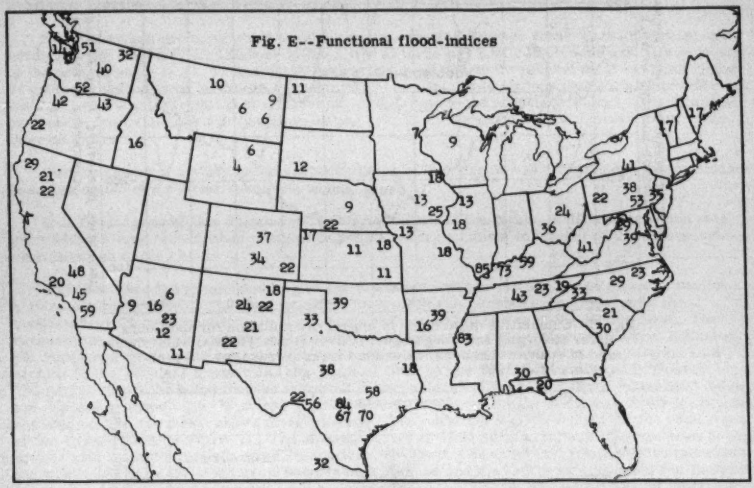


Fig. E--Functional flood-indices

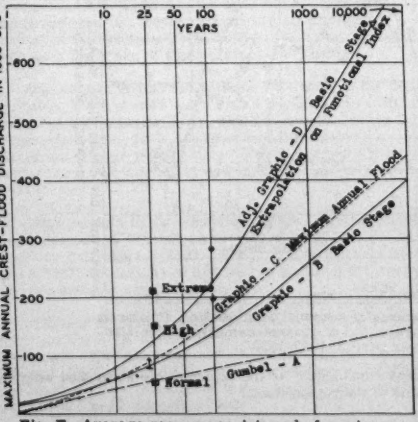


Fig. F--Average recurrence-interval of maximum annual flood-crests, East Fork Trinity River above Rockwall (Texas)

The above equations are for 100 per cent floods. The relationship of the constant of the flood of record to the constant, 10,000 or 230,000, when expressed as per cent is the index, or the "functional-flood index".

A map of the United States mainland with the functional-flood indices placed at the location of the flood of record is shown as Figure E. A number of the more important floods are so indexed; others should be added as regional studies progress.

As an example of the type of problem which arises, the series of the annual maximum flood-events of the East Fork of the Trinity River above Rockwall (Texas) is shown on Figure F. This watershed lies above Dallas just north of the east end of the Balcones escarpment, which is a region of intense rainstorms and flood-runoffs. It will be noted that the "functional indices" of Figure E which bound the region are 84,

58, with value of 39 in western Oklahoma and central Arkansas. The physical characteristics of the corresponding flood-source watersheds obviously will serve as a guide in the choice of a proper index for the East Fork of the Trinity River above Rockwall. As a matter of discussion, various values of the extrapolated curves are shown on Figure F.

Four curves have been fitted to data of theTrinity. Two deal with the annual maximum floods as peak-discharges. Liberty was taken to depart from Professor GUMBEL'S requirement of the mean daily discharge to that extent as the watershed is relatively small, 831 square miles. The period of record is 16.5 years, November, 1923, to April, 1940, which was called 16 years. The GUMBEL method was applied to the series, curve A, with the extrapolated result at 10,000 years indicated to be about 150,000 cfs or 19 per cent on the functional scale. In the solution of this series use was not made of the flood of 1922 which was unofficially estimated as 80,000 to 100,000 cfs. The fitted graphic curve (C) did take into account the position of the flood of 1922 and the estimated range of its magnitude. Its extrapolation reached 435,000 cfs, equivalent to a functional-flood index of 55 per cent, at 10,000 years.

Graphic solutions of the basic-stage series using all floods above 1290 cfs, approximately seven per year, were developed on double-log paper and transferred to Figure F. Curve B is fitted to the record data while Curve D was adjusted in terms of the precipitation-history and the relationship of the flood-runoffs of the long series of the Colorado River at Austin (Texas), which appeared to be quite similar to the long series of the Upper Mississippi River at Le Claire (Iowa). The B-curve was extrapolated to an index of 50 per cent while the D-curve was extrapolated to the maximum index of the region, 84 per cent. The extent to which the value of 84 per cent might be attained could be studied by the hydro-meteorological section of the United States Weather Bureau, particularly with respect to the possibility of as severe a storm as occurred to the southwest.

The graphic solution attains an asymptote, arbitrarily, at from 3,000 to 10,000 years. The projections of Figure F were extended on straight lines for the purposes of this discussion since the GUMBEL theory uses the semi-log paper with a straight-line projection. The point to be made here is the degree to which the hydrologist may use other approaches in the solution of a short series, which is admittedly outside the purview of the method of Professor GUMBEL. Of course, any extrapolation for 10,000 years utilizing as short a record as 16 years of observations must be highly uncertain.

On Figure F are discharge-values in squares with designations of Extreme, High, and Normal plotted on the 25-year average recurrence-interval ordinate. There are also two discharge-values plotted on the 100-year ordinate in circles. These values are taken from generalized regional maps made to assist field-engineers in the estimate of flood-discharges by other hydrologists. The opinion they represented is dated about 1938 and 1940, respectively.

Recommendations--(1) It is recommended that work be initiated as soon as possible to extend this research to encompass the concepts of the basic stage in as equally sound and rigorous a manner as Professor GUMBEL used in developing the procedure for the series of the annual maximum daily means.

(2) That provision be made to secure the compilation of sufficiently accurate tables of the probability-function, $e^{-e^{-y}}$, the theoretical recurrence-interval, T, and the control-function, σ, all three in terms of y; and in addition, y as a function of the probability, W*. The equations for the above follow.

$$(1)\ W^* = e^{-e^{-y}} \qquad (18)\ \sigma\sqrt{n} = e^{y}\sqrt{e^{e^{-y}} - 1}$$

$$(21)\ T = 1/(1 - e^{-e^{-y}}) \qquad (22)\ y = -\log_e(-\log_e W^*)$$

These tables can then be incorporated with instructions for field-personnel for use in the solution of flood-series.

(3) The pertinent researches of (1) above can be advanced as time and funds will permit. The tables of (2) above will be valuable aids to the hydrologist and others.

Acknowledgments--Acknowledgment is made for assistance in the regional precipitation-indices studies to Messrs. H. W. RICE and FRANK GRABSKI and to the latter for the preparation of the graphs.

E. J. GUMBEL (communicated)--Mr. KIMBALL insists rightly on the importance of the relation between m and $n\lambda$. This relation has a bearing on the determination of the constant u and on

the plotting of the observed curves. For the determination of the constant u by formula (16) the question whether to choose $m = (n\lambda + 1/2)$ or $m = (n\lambda + \lambda)$ is not decisive. These formulas lead to different values for the mode and for the theoretical floods. But the calculations made since finishing the manuscript have shown that the differences for the usual number of observations would not even be visible in the graphs. Visible differences exist only for very small numbers of observations.

On the other hand, the choice of the relation between m and $n\lambda$ has a large influence on the plotting of the observations. The exceedence-intervals $'T(x_m)$ obtained from $m = n\lambda$, the recur-

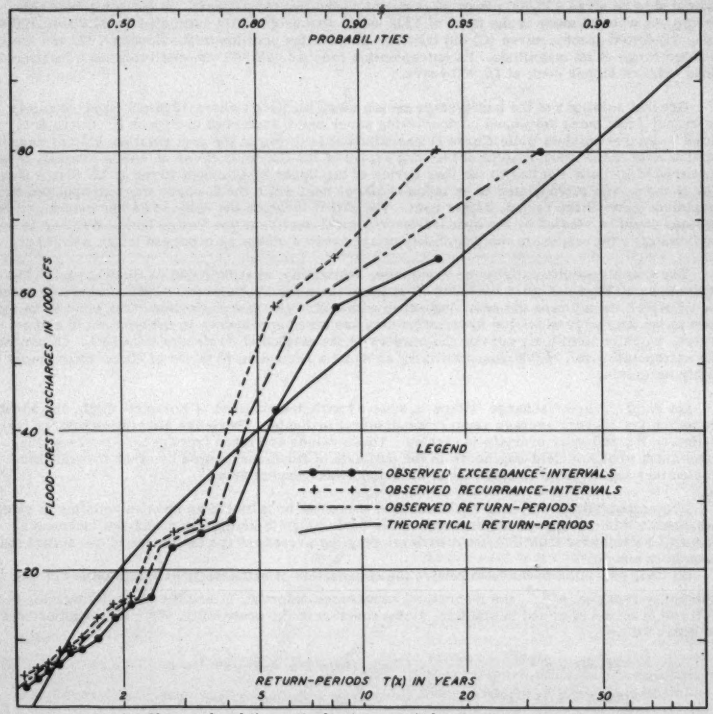


Fig. 7--Observed and theoretical return-periods, East Fork Trinity River

rence-intervals $'T(x_m)$ obtained from $m = (n\lambda + 1)$, and HAZEN'S observed return-period $T(x_m) = n/(n - m + 1/2)$ obtained from $m = (n\lambda + 1/2)$ may differ widely for numbers of m which are of the n-size. This is due to the fact that the exceedence-interval, being infinite for $m = n$, is not defined for the largest flood-discharge. The corresponding recurrence-interval is only n, whereas HAZEN'S value is 2n. The use of $m = (n\lambda + \lambda)$ for the observations, being too complicated, is not advised.

The exceedence-intervals, the recurrence-intervals, and the observed return-periods are shown in Figure 7 which deals with the flood-crest discharges, East Fork of Trinity River, 1922,

1924-39, studied by R. S. GOODRIDGE. The flood of April 1922, previous to the installation of a gaging-station, was assumed to have been 80,000 cfs. The number of observations is n = 17. The observed return-periods are, of course, contained between the two other observed curves. The last value of the observed return-periods 2n cannot be used, as no statistical device is able to increase the number of observations beyond n.

As the number of observations is very small, we have calculated the constant through the classical procedure which leads to u = 13.393 and $(1/\alpha = 18.265$. These values are based on the assumption made for 1922. The theoretical curve is nearly linear. The fit of the theory to the observations is not so good as in our previous examples. But no better fit may reasonably be expected for such a small number of observations. The extrapolation gives a flood-crest of 97,000 cfs for the next 100 years. We do not think it advisable to extrapolate for longer periods as only 16 records are given.

STUDIES IN THE BALANCED WATER-ECONOMY OF EXPERIMENTAL DRAINAGE-AREAS

C. R. Hursh, M. D. Hoover, and P. W. Fletcher

Watershed-management studies require drainage-areas that are independent hydrologic units having distinctive land-use patterns. Such studies are in progress on the Coweeta Experimental Forest in Macon County, North Carolina, by the United States Department of Agriculture, Forest Service. This 4,600-acre experimental area was selected specifically for the study of the hydrologic cycle in relation to the practical problems of land-management for water-yield. The area contains 30 small drainages with continuous flow. The average annual rainfall of 70 inches is distributed throughout the year. Mean annual temperature is 55° F. Soils are deep and permeable, but water-tables are sufficiently high to be observed in shallow wells. The natural growth is composed of deciduous trees with abundant shrubs and minor vegetation. Topography and stream-pattern favor the establishment of independent experimental units.

Evaluating the effects of land-use on water-cycle factors, although difficult for large areas, becomes more feasible on small experimental drainages. Hydrologic measurements are first made over a period of five years or more under natural forest-vegetation before changes in land-use are made. Records are compared before and after the change. Also, because half of the total number of drainage-areas are held as controls, comparative checks may be made with similar drainages selected as controls for each study.

For practical purposes, the most important single measurement is that of seasonal yield of ground-water and storm-runoff. However, to understand water-yield it is necessary to evaluate other factors of the water-cycle that relate specifically to the drainage-area. These include the amount of soil-moisture and ground-water in storage, together with current evaporation and transpiration.

The present paper discusses the problem of keeping accounts of the essential water-cycle factors for experimental drainage-areas. It is recognized that for practical purposes water-accounts should be kept storm by storm and this is the ultimate objective of the study. However, for a general consideration of the problem, monthly and annual balances are more suitable than are individual storm-values.

To illustrate methods, data from a representative experimental drainage-area of approximately 40 acres at an elevation of 2,200 to 3,200 feet are used. The vegetative cover is a hardwood forest not grazed, cut, or burned for at least 20 years.

Water-cycle measurements--In general, water-cycle measurements relate to the circulating water-capital of a drainage-area within a single water-year. This capital may be only a portion of the total amount of water on the drainage as there is always a base quantity of water present. Current balances are considered to account for water above this unmeasured base. Nevertheless, there is always the possibility that a part of this base-quantity of water can enter into the yearly balance. For this reason solution of unknowns by residuals alone may be unsatisfactory. The problem is to devise checks on those values known occasionally to draw upon the base water-capital of the drainage. With these checks, though they be only approximate, it may be possible to interpret plus or minus residual accumulations, and thus carry forward usable balances from one year to the next. The principal checks used for this purpose are the amount of ground-water and soil-moisture in storage within the soil-profile. These measurements, combined with independent

estimates of evaporation and transpiration both by physical constants and by the use of mean yearly values also serve as a basis for studying the continuous water-economy of the experimental drainage-area. For temperate humid climates, it is also conceivable that the seasonal relationships of precipitation, runoff, and storage are so definite that they in themselves furnish a good basis for checking the water-cycle.

The water-year--For temperate climates, a study of the relationship of rainfall to runoff over long periods indicates that the times of minimum flow generally succeed each other by approximately 12 months. These periods are considered as the end of one water-year and the beginning of the next. Similarly, a period of annual maximum stream-flow can be recognized, which, if based on ground-water discharge, represents a value of maximum ground-water storage. PARKER [see 1 of "References" at end of paper] expresses his opinion "if the period at which the water stored up in the ground is at a maximum could be definitely observed, the relations of the rainfall to runoff for the intervals between these maxima would be more constant than for any other period." He recognizes, however, the difficulties of observing periods of maximum ground-water storage, and also that such periods may be more irregular in time than are periods of low flow.

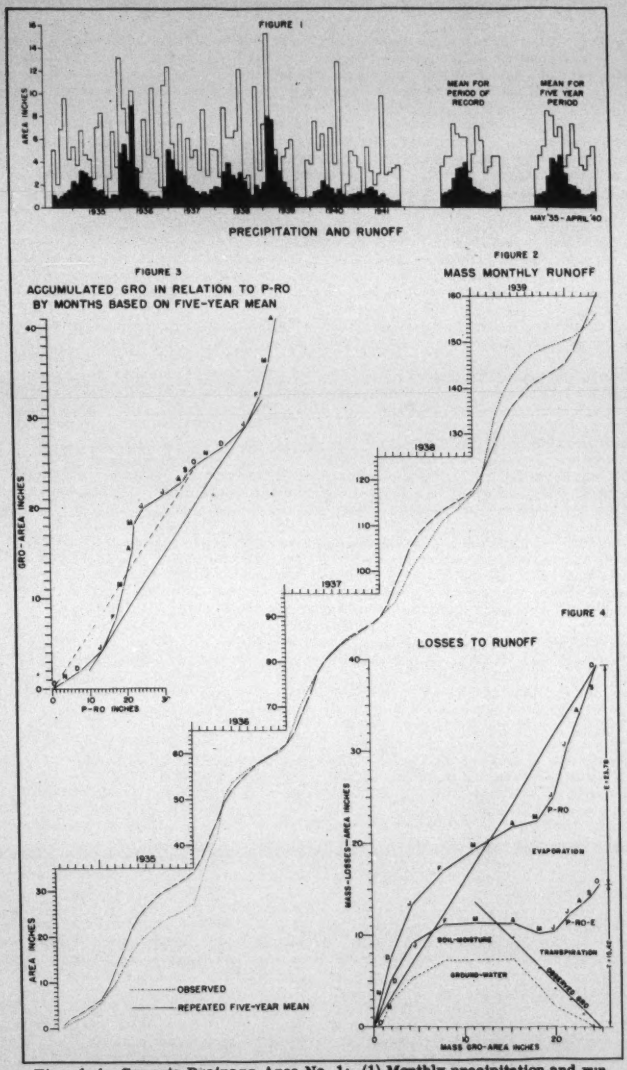
Both RAFTER [2] and HOUK [3] have recognized the water-year as divided into three periods, namely, replenishment of soil-moisture, storage of ground-water, and the growing period. The actual months covered by these essential divisions of the water-year will depend on the local climatic conditions. RAFTER used November 30 as the end of his water-year, and as the end of the replenishing period begun in September. He then considered December to May as the storage-period, which indicates that this division is made for a region of cold winters and heavy snow. For the Miami Valley, HOUK thought it more feasible to consider the months from October to December as the replenishing period, and January to April as the storage-period. HOYT [4] et al, reporting data for the Skunk River Basin in Iowa, derived approximate changes in soil-moisture by months, and recognized the month of September as beginning the replenishment-period. Their computations, covering a five-year period [Table 61], show [Column (9)] that the residual soil-moisture values when carried as a summation, tend to balance out to zero during the early autumn for the years of normal precipitation. It is also apparent in Columns (8) and (10), Table 61, that the total accretion to ground-water tends to balance ground-water runoff. VERMEULE [5] in his early classic on monthly and seasonal runoff-characteristics of streams summarized his data into the four seasons and then combined them into two periods, one from December to May, the other from June to November.

Runoff-precipitation relationships--A lineal relationship of plotted precipitation-summations and annual runoff has been frequently discussed. Values for individual months are known to fluctuate around the general slope of the mass-trend in a fairly regular pattern. The integrated hydrograph of monthly flow used in computing seasonal discharge is an expression of this fairly regular pattern of the monthly departure from the general slope of the line representing the summations of runoff.

Using the values shown in Figure 1, the summation of runoff has been expressed by months for a five-year period in Figure 2. Attempts to draw a straight trend line through the monthly values for different years indicate that the best fit comes during early fall or late spring months. It is believed that these are significant points in the water-year indicating fundamental changes in the seasonal relationships. Although periods of minimum or maximum storage will not be reached in every water-year, it is probable that the high precipitation and relatively high summer temperatures of the Coweeta Experimental Forest produce a more nearly uniform range of storage within the water-year than occurs in many other sections of the country.

Figure 2 shows also a repetition of the monthly means for the five-year period. The monthly sequence for 1937 is quite similar to the mean year monthly sequence. The two lines were approximately fitted for this year and used as a basis for comparing the remaining years. Considerable difference occurs between the mean and the monthly sequence for other years. However, both lines tend to coincide at least for a portion of the year, most commonly in the winter or spring months.

It is reasonable to expect that transpiration and other factors of the water-cycle controlled by biological activities remain fairly constant on a drainage-area where a natural vegetative cover has become established. The amount of plant-growth tends to be the same each year. Consequently, it may be expected that the mean annual transpiration-requirements over a period of years will remain the same. The physical constants that govern evaporation from the soil do not change rapidly under undisturbed natural conditions of a drainage-area. Neither do soil--profile-storage opportunities change from year to year unless some unusual disturbance takes place at the surface.



Figs. 1-4--Coweeta Drainage-Area No. 1: (1) Monthly precipitation and runoff; (2) summation of runoff by months; (3) relation of ground-water runoff to ground-water storage; (4) graphic water-cycle analysis for mean year

Consequently, there are numerous reasons why water-accounts for a small drainage-area in a region of high precipitation should tend to balance annually for years of normal precipitation. When the water-accounts do not balance, the plus or minus water in storage at the end of the water-year is an expression of the annual deviation from the normal in precipitation or temperature.

The integrated hydrographs, Figure 2, have been drawn on a basis of runoff over months. This general diagram of runoff does not change greatly for the Coweeta Experimental Forest drainages when the summations of runoff are expressed over summations of either total rainfall or net effective rainfall. Here the slope-relationships show the uniform monthly deviations from the mean yearly slope. This type of diagram serves chiefly to indicate possible relationships not otherwise apparent, but may also serve for the indirect solution of unknown monthly values.

If the water-cycle does tend to balance annually in a region of high rainfall, it would be expected that the trend of the mean annual slope of such a relationship as the sums of GRO/net rainfall is characteristic for the individual drainage-area. Monthly changes occur in such a uniform pattern around the yearly slope of this relationship for Coweeta experimental drainages as to suggest that marked seasonal changes may serve as a check in water-cycle balances. A graphic expression of a monthly storage-discharge relationship is furnished by plotting GRO over an expression of losses to runoff such as P-SRO-E or P-RO, as shown in Figure 3.

Figure 3 shows the summation of the mean values of GRO expressed in relation to the summation of P-RO for the same month. These are from the same values of RO as shown in the mean curve of Figure 2. A plotting of GRO over P-RO for the preceding month may give a more significant curve. By deviation from the yearly mean slope, the monthly slopes show the degree to which GRO is greater or less than P-RO.

The values for the month of May indicate that GRO is almost independent of storage as expressed by P-RO. Storage opportunities are normally at a minimum and ground-water runoff becomes more directly related to precipitation than at any other period of the year.

To indicate exact seasonal storage-periods for the high rainfall-belt of the Southern Appalachians is an arbitrary procedure insomuch as replenishment of soil-moisture and also storage of ground-water will take place in any of the summer months when high rainfall results from tropical hurricane influences from the Gulf or South Atlantic. However, the concept of seasonal storage-periods is imperative to interpreting water-cycle problems.

The GRO/P-RO relationship shown in Figure 3 becomes the familiar mass-curve of P-RO when GRO becomes the X-axis (Fig. 4), or when P-RO is plotted over a uniform time-scale (Fig. 5).

Data for the mean curve on Figure 2, and for Figures 3, 4, and 5 are given in Table 1. The mass-expressions of Figures 4 and 5 are exactly the same as the tabulations of sums in the monthly accounting system used in Tables 1 and 2.

Of a number of methods for carrying forward a monthly record of water in storage on experimental drainage-areas, the one shown in Table 1 appears to be most practical. The ground-water storage-curve as described by SNYDER [6] is the basis for separating ground-water, Column (8), from soil-moisture, Column (12). The area-inches of ground-water storage given in Column (8) is an amount above the base of the storage-curve which for this drainage-area was drawn beginning 0.50 csm equals zero inch. The permanent base soil-moisture on the drainage-area is not known. Column (10) gives the sum of transpiration (P-RO-E) corrected for temperature through the use of MEYER'S [7] curve of transpiration. These values are redistributed as indicated by Columns (11) and (12).

The values given in Table 1 represent only the circulating water-capital furnished by current precipitation. No gain or loss is shown over the amount of precipitation for the mean year, although Column (8) and Column (12) are out of balance by 0.17 inch. Table 2 shows a trial-balance for seven years in which there is always a plus or minus carry-over of ground-water in storage and soil-moisture from one year into the next.

Figure 4 shows the essential water-cycle components that must be accounted for in keeping current records of circulating water-capital. The GRO storage-base [Column (8), Table 1], is continuous from one year into the next and constitutes a measurable reference that may be quickly determined by the use of the storage-curve. The observed GRO of Figure 4 comes from Column (2) of Table 1. For this mean year GRO from May to October may be considered to come largely from ground-water stored before May 1. Consequently, the depletion of observed GRO (Fig. 4)

Table 1--Mean monthly balances of sub-surface storage for 5-year period, May, 1935, to May, 1940, Coweeta Experimental Forest, Drainage-Area No. 1

(All values in area-inches)

Month	P	GRO	RO	Meyer's E	(P - RO - E)		Storage							t
							Ground-water change from storage-curve		Soil-moisture change					
									Soil-moisture + T	T		Soil-moisture		
	(1)	(2)	(3)	(4)	Month (5)	Sum (6)	Month (7)	Sum (8)	(6)-(8) (9)	Month (10)	Sum (11)	(9)-(11) (12)	Month (13)	(14) °F
Nov.	4.50	0.90	1.09	1.23	2.18	2.18	0.39	0.39	1.79			1.79	1.79	45.7
Dec.	5.34	1.10	1.29	1.14	2.91	5.09	2.43	2.82	2.27			2.27	0.48	38.1
Jan.	8.43	2.38	2.67	1.79	3.97	9.06	2.40	5.22	3.84			3.84	1.57	37.7
Feb.	7.91	3.34	4.11	1.71	2.09	11.15	2.12	7.34	3.81			3.81	-0.03	40.7
Mar.	6.15	3.52	3.87	2.09	0.19	11.34	0.05	7.39	3.95			3.95	0.14	47.5
Apr.	7.02	4.08	4.54	2.54	-0.06	11.28	0.08	7.47	3.81	1.45	1.45	2.36	-1.59	53.3
May	3.56	2.85	2.94	1.77	-1.15	10.13	-3.03	4.44	5.69	2.14	3.59	2.10	-0.26	61.6
June	4.56	1.84	1.94	2.36	0.26	10.39	-2.20	2.24	8.15	2.67	6.26	1.89	-0.21	68.6
July	7.26	1.54	1.81	3.55	1.90	12.29	0.18	2.42	9.87	2.91	9.17	0.70	-1.19	71.2
Aug.	5.24	1.38	1.48	2.66	1.10	13.39	-1.62	0.80	12.59	2.78	11.95	0.64	-0.06	71.4
Sep.	3.74	0.98	1.08	1.72	0.94	14.33	-0.71	0.09	14.24	2.20	14.15	0.09	-0.55	66.2
Oct.	6.28	0.88	0.97	1.22	1.09	15.42	-0.26	-0.17	15.59	1.27	15.42	0.17	0.08	56.2
Total	66.99	.....	27.79	23.78	.....	.....	.....	.....	.....	15.42	.....	.....	.....	.....

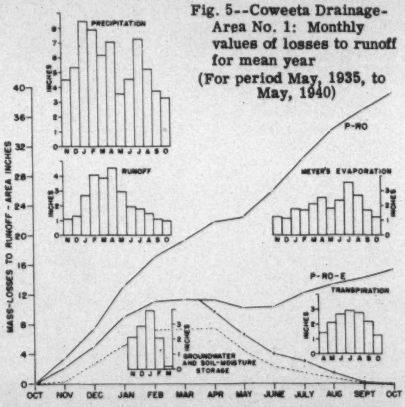


Fig. 5--Coweeta Drainage-Area No. 1: Monthly values of losses to runoff for mean year (For period May, 1935, to May, 1940)

may be used as the approximate base for taking off sums of transpiration from the (P-RO-E) curve of a mean year. However, the values obtained must be redistributed on the basis of temperature. This may be done by the use of MEYER'S [7] curves of transpiration in Column (10), the summation values of which are shown as heavy triangles along the curve of observed GRO depletion. In Figure 5, only this adjusted base for scaling off summations of transpiration is shown.

For other than the mean year, the sums in Column (10) of Table 2, for months of April to October when redistributed as transpiration, Column (11), give a residual which is carried over into the following year as a summation of soil-moisture, Column (15). At the beginning of Table 2 no soil-moisture was carried over from water-year 1933-34, but residual values of soil-moisture appear in all other years. These residuals are no more accurate than the estimates on which they are based, but with few exceptions they are in good agreement with field-observations.

Table 2--Monthly accounts of circulating water capital for the 7-year period, November 1934, to October 1941, Coweeta Experimental Forest, Drainage-Area No. 1

(All values in area-inches)

Month	P	GRO	RO	Meyer's E	(P-RO-E)		Storage									t
							Ground-water			Soil-moisture						
							Change from storage-curve		Total	Soil-moisture + T	Transpiration		Change		Total	
					Month	Sum	Month	Sum	Sum	(6)-(8)	Month	Sum	(10)-(12)	Month	Sum	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
1934-5									1.49[b]							°F
Nov.	9.62	0.94	1.24	2.10	6.28	6.28	4.13	4.13	5.62	2.15			2.15	2.15	2.15	45.7[a]
Dec.	4.21	1.38	1.52	1.00	1.69	7.97	-1.36	2.77	4.26	5.20			5.20	3.05	5.20	38.1[a]
Jan.	5.34	1.88	2.33	1.50	1.51	9.48	0.61	3.38	4.87	6.10			6.10	0.90	6.10	37.7[a]
Feb.	3.70	1.92	2.02	1.25	0.43	9.91	0.17	3.55	5.04	6.36			6.36	0.26	6.36	40.7[a]
Mar.	6.78	2.93	3.22	2.25	1.31	11.22	2.95	6.50	7.99	4.72			4.72	-1.64	4.72	47.5[a]
Apr.	4.63	2.87	3.00	1.90	-0.27	10.95	-0.99	5.51	7.00	5.44	1.45	1.45	3.99	-0.73	3.99	53.3[a]
May	4.23	2.55	2.65	2.05	-0.47	10.48	-2.06	3.45	4.94	7.03	2.14	3.59	3.44	-0.55	3.44	61.6[a]
June	2.52	1.73	1.76	1.50	-0.74	9.74	-1.99	1.46	2.95	8.28	2.67	6.26	2.02	-1.42	2.02	67.0
July	7.03	1.27	1.41	3.50	2.12	11.86	-1.08	0.38	1.87	11.48	2.91	9.17	2.31	0.29	2.31	72.0
Aug.	8.25	1.24	1.49	3.75	3.01	14.87	0.41	0.79	2.28	14.08	2.78	11.95	2.13	-0.18	2.13	71.4[a]
Sep.	1.02	0.99	1.00	0.60	-0.58	14.29	-1.71	-0.92	0.57	15.21	2.20	14.15	1.06	-1.07	1.06	66.2[a]
Oct.	2.50	0.72	0.76	1.10	0.64	14.93	0.13	-0.79	0.70	15.72	1.27	15.42	0.30	-0.76	0.30	55.7
1935-6																
Nov.	6.65	0.86	1.09	2.00	3.56	3.56	0.70	0.70	1.40	2.86			2.86	2.86	3.16	48.7
Dec.	3.52	0.97	1.01	0.70	1.81	5.37	0.32	1.02	1.72	4.35			4.35	1.49	4.65	31.0
Jan.	13.75	3.46	4.70	1.45	7.60	12.97	5.83	6.85	7.55	6.12			6.12	1.77	6.42	33.6
Feb.	8.66	4.86	5.53	1.65	1.48	14.45	2.45	9.30	10.00	5.15			5.15	-0.97	5.45	36.3
Mar.	6.56	3.79	3.98	2.20	0.38	14.83	0.34	9.64	10.34	5.19			5.19	0.04	5.49	47.8
Apr.	10.22	7.96	8.90	3.40	-2.08	12.75	0.63	10.27	10.97	2.48	1.45	1.45	1.03	-4.16	1.33	53.8
May	2.40	3.20	3.41	1.35	-2.36	10.39	-5.45	4.82	5.52	5.57	2.14	3.59	1.98	0.95	2.28	62.4
June	3.13	1.39	1.53	1.85	0.25	10.14	-3.76	1.06	1.76	9.08	2.67	6.26	2.82	0.84	3.12	69.7
July	7.70	1.13	1.33	3.80	2.57	12.71	0.29	1.35	2.05	11.36	2.91	9.17	2.19	-0.63	2.49	73.2
Aug.	4.58	0.75	0.81	2.35	1.42	14.13	-1.84	-0.49	0.21	14.62	2.78	11.95	2.67	0.48	2.97	71.6
Sep.	10.45	0.55	0.95	4.25	5.25	19.38	1.91	1.42	2.12	17.96	2.20	14.15	3.81	1.14	4.11	68.7
Oct.	4.33	0.90	0.98	1.75	1.60	20.98	-1.60	-0.18	0.52	21.16	1.27	15.42	5.74	1.93	6.04	58.8
1936-7																
Nov.	1.70	0.76	0.77	0.60	0.33	0.33	0.26	0.26	0.78	0.07			0.07	0.07	6.11	45.8
Dec.	10.77	1.30	1.75	1.95	7.07	7.40	9.56	9.82	10.34	-2.42			-2.42	-2.49	3.62	43.9
Jan.	12.33	4.39	4.92	1.80	5.61	13.01	0.42	10.24	10.76	2.77			2.77	5.19	8.81	37.7
Feb.	5.58	3.84	4.09	1.60	-0.11	12.90	-0.96	9.28	9.80	3.62			3.62	0.85	9.66	39.0
Mar.	2.78	3.04	3.24	1.10	-1.56	11.34	-2.27	7.01	7.53	4.33			4.33	0.71	10.37	45.3
Apr.	7.31	2.71	3.11	2.65	1.55	12.89	0.83	7.84	8.36	5.05	1.45	1.45	3.60	-0.73	9.64	53.3
May	2.34	2.70	2.72	1.35	-1.73	11.16	-3.45	4.39	4.91	6.77	2.14	3.59	3.18	-0.42	9.22	62.4
June	6.08	1.73	1.83	3.00	1.25	12.41	-0.86	3.53	4.05	8.88	2.67	6.26	2.62	-0.56	8.66	69.6
July	4.37	1.60	1.64	2.35	0.38	12.79	-1.07	2.46	2.98	10.33	2.91	9.17	1.16	-1.46	7.20	69.9
Aug.	5.02	1.26	1.30	2.55	1.17	13.96	-0.65	1.81	2.33	12.15	2.78	11.95	0.20	-0.96	6.24	71.6
Sep.	3.22	1.00	1.05	1.50	0.67	14.63	-1.22	0.59	1.11	14.04	2.20	14.15	-0.11	-0.31	5.93	63.4
Oct.	8.57	1.01	1.34	2.70	4.53	19.16	0.94	1.53	2.05	17.63	1.27	15.42	2.21	2.32	8.25	53.4
1937-8																
Nov.	2.75	1.00	1.04	0.80	0.91	0.91	0.07	0.07	2.12	0.84			0.84	0.84	9.09	43.3
Dec.	5.09	1.17	1.44	1.20	2.45	3.36	2.37	2.44	4.49	0.92			0.92	0.08	9.17	37.9
Jan.	5.03	1.56	1.74	1.50	1.79	5.15	0.18	2.62	4.67	2.53			2.53	1.61	10.78	38.6
Feb.	2.66	1.55	1.60	1.10	-0.04	5.11	-1.03	1.59	3.64	3.52			3.52	0.99	11.77	46.0
Mar.	8.75	2.29	3.07	2.90	2.78	7.89	4.11	5.70	7.75	2.19			2.19	-1.33	10.44	51.6
Apr.	6.12	3.57	3.89	2.40	-0.17	7.72	0.35	6.05	8.10	1.67	1.45	1.45	0.22	-1.97	8.47	54.6
May	6.11	2.68	2.79	2.70	0.62	8.34	-1.49	4.56	6.61	3.78	2.14	3.59	0.19	-0.03	8.44	62.0
June	6.70	2.23	2.41	3.10	1.19	9.53	-1.81	2.75	4.80	6.78	2.67	6.26	0.52	0.33	8.77	66.5
July	12.07	2.13	3.04	5.30	3.73	13.26	4.12	6.87	8.92	6.39	2.91	9.17	-2.78	-3.30	5.47	70.7
Aug.	2.45	2.49	2.51	1.50	-1.56	11.70	-4.87	2.00	4.05	9.70	2.78	11.95	-2.25	0.53	6.00	72.8
Sep.	2.85	1.53	1.57	1.45	-0.17	11.53	-1.68	0.32	2.37	11.21	2.20	14.15	-2.94	-0.69	5.31	65.7
Oct.	0.18	1.09	1.09	0.15	-1.06	10.47	-0.80	-0.48	1.57	10.95	1.27	15.42	-4.47	-1.53	3.78	55.8

Column (9) has also been introduced in Table 2 to carry forward a continuous value of total ground-water. The sum of Columns (9) and (15) represents the amount of circulating water in storage at the end of each month after evaporation and transpiration have been accounted for. During the course of the month both transpiration and evaporation have been a part of soil-moisture. Consequently, the values given in Column (15) must be thought of as being one to four inches higher than actually shown to account for transient evaporation and transpiration not appearing in final monthly balances.

Table 2--Monthly accounts of circulating water capital for the 7-year period, November 1934, to October 1941, Coweeta Experimental Forest, Drainage-Area No. 1--Concluded

(All values in area-inches)

Month	P	GRO	RO	Meyer's E	(P-RO-E)		Storage									t
							Ground-water			Soil-moisture						
							Change from storage-curve		Total	Soil-moisture + T	Transpiration		Change		Total	
					Month	Sum	Month	Sum	Sum	(6)-(8)	Month	Sum	(10)-(12)	Month	Sum	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
																°F
1938-9																
Nov.	10.57	1.24	1.91	2.15	6.51	6.51	1.30	1.30	2.87	5.21			5.21	5.21	8.99	47.0
Dec.	3.19	1.40	1.54	0.80	0.85	7.36	0.11	1.41	2.98	5.95			5.95	0.74	9.73	38.6
Jan.	7.30	1.73	2.13	2.00	3.17	10.53	5.18	6.59	8.16	3.94			3.94	-2.01	7.72	39.9
Feb.	15.20	5.48	7.98	2.35	4.87	15.40	7.97	14.56	16.13	0.84			0.84	-3.10	4.62	44.4
Mar.	7.61	7.13	7.65	2.50	-2.54	12.86	-2.88	11.68	13.25	1.18			1.18	0.34	4.96	48.8
Apr.	5.03	4.35	4.53	2.00	-1.50	11.36	-3.75	7.93	9.50	3.43	1.45	1.45	1.98	0.80	5.76	52.7
May	2.74	3.13	3.15	1.40	-1.81	9.55	-2.68	5.25	6.82	4.30	2.14	3.59	0.71	-1.27	4.49	59.9
June	4.39	2.11	2.18	2.40	-0.19	9.36	-2.60	2.65	4.22	6.71	2.67	6.26	0.45	-0.26	4.23	70.3
July	5.15	1.58	1.65	2.80	0.70	10.06	-1.38	1.27	2.84	8.79	2.91	9.17	-0.38	-0.83	3.40	70.1
Aug.	5.91	1.18	1.27	3.15	1.49	11.55	-1.15	0.12	1.69	11.43	2.78	11.95	-0.52	-0.14	3.26	69.7
Sep.	1.16	0.85	0.85	0.75	-0.44	11.11	-0.83	-0.71	0.86	11.82	2.20	14.15	-2.33	-1.81	1.45	66.8
Oct.	0.82	0.69	0.70	0.45	-0.33	10.78	0.00	-0.71	0.86	11.49	1.27	15.42	-3.93	-1.60	-0.15	57.4
1939-40																
Nov.	0.83	0.65	0.66	0.35	-0.18	-0.18	-0.36	-0.36	0.50	0.18			0.18	0.18	0.03	43.6
Dec.	4.13	0.66	0.73	1.05	2.35	2.17	-0.21	-0.57	0.29	2.74			2.74	2.56	2.59	38.9
Jan.	3.75	0.75	0.85	0.85	2.05	4.22	0.41	-0.16	0.70	4.38			4.38	1.64	4.23	24.8
Feb.	7.47	0.99	1.34	1.80	4.33	8.55	2.17	2.01	2.87	6.54			6.54	2.16	6.39	37.6
Mar.	5.03	1.33	1.43	1.70	1.90	10.45	0.94	2.95	3.81	7.50			7.50	0.96	7.35	44.0
Apr.	6.41	1.80	2.28	2.25	1.88	12.33	2.36	5.31	6.17	7.02	1.45	1.45	5.57	-1.93	5.42	52.1
May	1.88	1.87	1.88	1.05	-1.05	11.28	-2.82	2.49	3.35	8.79	2.14	3.59	5.20	-0.37	5.05	58.3
June	6.95	1.43	1.59	3.15	2.21	13.49	-1.27	1.22	2.08	12.27	2.67	6.26	6.01	0.81	5.86	67.0
July	3.79	1.15	1.17	2.10	0.52	14.01	-1.10	0.12	0.98	13.89	2.91	9.17	4.72	-1.29	4.57	69.1
Aug.	12.76	1.00	1.57	4.90	6.29	20.30	2.93	3.05	3.91	17.25	2.78	11.95	5.30	0.58	5.15	69.9
Sep.	0.64	1.03	1.04	0.40	-0.80	19.50	-2.85	0.20	1.06	19.30	2.20	14.15	5.15	-0.15	5.00	62.4
Oct.	2.06	0.82	0.84	0.90	0.32	19.82	0.58	0.78	1.64	19.04	1.27	15.42	3.62	-1.53	3.47	55.3
1940-1																
Nov.	4.90	0.90	1.03	1.40	2.47	2.47	-0.16	-0.16	1.48	2.63			2.63	2.63	6.10	45.1
Dec.	4.48	1.03	1.12	1.20	2.16	4.63	0.72	0.56	2.20	4.07			4.07	1.44	7.54	42.7
Jan.	3.47	1.20	1.28	1.15	1.04	5.67	0.19	0.75	2.39	4.92			4.92	0.85	8.39	38.9
Feb.	1.55	1.08	1.10	0.70	-0.25	5.42	-0.27	0.48	2.12	4.94			4.94	0.02	8.41	34.9
Mar.	5.24	1.48	1.58	1.65	2.01	7.43	1.22	1.70	3.34	5.73			5.73	0.79	9.20	41.4
Apr.	3.19	1.62	1.69	1.50	0.00	7.43	0.12	1.82	3.46	5.61	1.45	1.45	4.16	-1.57	7.63	55.7
May	1.96	1.37	1.39	1.10	-0.53	6.90	-1.41	0.41	2.05	6.49	2.14	3.59	2.90	-1.26	6.37	61.1
June	2.95	0.87	0.89	1.70	0.36	7.26	-0.86	-0.45	1.19	7.71	2.67	6.26	1.45	-1.45	4.92	68.0
July	9.76	0.96	1.17	4.50	4.09	11.35	-0.25	-0.70	0.94	12.05	2.91	9.17	2.88	1.43	6.35	73.2
Aug.	2.83	0.67	0.69	1.60	0.54	11.89	-1.28	-1.98	-0.34	13.87	2.78	11.95	1.92	-0.96	5.39	72.5
Sep.	3.02	0.48	0.50	1.60	0.92	12.81	-0.12	-2.10	-0.46	14.91	2.20	14.15	0.76	-1.16	4.23	67.6
Oct.	3.39	0.38	0.42	1.50	1.47	14.28	-0.04	-2.14	-0.50	16.42	1.27	15.42	1.00	0.24	4.47	59.8

[a]Means for record period. [b]Observed ground-water October 31, 1934.

Use of Table 2--The accounting procedure shown in Table 2 will give a current value of ground-water and soil-moisture in storage in the absence of well-records and soil-moisture determinations. Where soil-moisture determinations are available they serve as a basis for correcting the tabular values. Frequently, however, in a region where periods of continuous daily rainfall occur, adequate moisture-sampling of the entire soil-profile becomes an impossible task. During such periods the values in Table 2 may be carried forward by days for special periods, or storm by storm, using computed corrections for evaporation and transpiration and other field-moisture losses. The feasibility of this procedure has been recently pointed out by LINSLEY and ACKERMANN [8].

The greatest practical value in Table 2 should be in showing actual circulating values of soil-moisture and ground-water in storage. The lack of sensitivity of ground-water levels to rainfall before soil-moisture replenishment has taken place shows up throughout the Table. Rapid rises in ground-water may be expected to take place only when soil-moisture is at a maximum. These comparative values of soil-moisture and ground-water will be generally used for computing current storage-opportunity in the soil-profile for forecasting runoff.

Because the monthly balance in Table 2 is made at the end of each month, the current values may be extended into a daily or storm-by-storm analysis by beginning with the last monthly balances. In any case monthly balances serve as a check on storm-analyses. Further studies using short-period analyses are now in progress for the Coweeta drainages.

The monthly values shown in Table 2 may be obtained directly without the use of sums. However, sums are advantageous as a constant check on errors of tabulation which are common in handling negative quantities. Sums lend themselves well to calculation by machine.

The most outstanding error in the trial-balances given in Table 2 is that the storage-curve obtained directly from the normal curve of ground-water depletion, and used to derive the ground-water change, Column (7), apparently does not apply to the months of exceptionally high rainfall. Either this is the case, or else MEYER'S values of transpiration are too high for these months. Both may be true. As a result, negative values appear in Column (13) which cannot be explained. Nevertheless, these unexplained values serve as the clue for locating the inaccuracies in the estimates of Columns (7) and (4). An effort is being made to find and correct these errors.

So far as can be determined, serious errors appear chiefly for months of ten inches of precipitation or more. Elsewhere the Table appears to check well with field-observations. A close field-check upon such exceptional periods as September to December, 1939, when precipitation was far below normal, bears out the low values in Column (8). In August, September, and October, 1941, GRO actually fell below the 0.5 csm zero-point of the storage-curve, and the readings of ground-water storage were taken from an extended curve. As a whole, Table 2 in its present form is of more value in presenting a check-method of accounting for continuous hydrologic phenomena, rather than a completely accurate water-storage analysis for the drainage-area studied. In the latter sense it must be considered more as a progress-report and a trial-balance which requires numerous corrections.

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DISCUSSION

L. K. SHERMAN (Chicago, Illinois)--The whole is equal to the sum of all of the parts. This axiom, referred to the volume of water falling on a drainage-basin, includes the storage-equation: Inflow = Outflow $\pm$ storage.

The whole is a known quantity and the equation may be used to determine any single residual part if the other parts are determinate. The residual here in question is the volume of ground-water storage. The authors have made a graphical presentation of the problem which is ingenuous and has the beauty of clearness and simplicity.

The authors' work is confined (perhaps fortunately) to a basin where the period of ground-water accretion does not coincide or conflict with the season of transpiration. Perhaps a similar methodology could be applied to other basins where transpiration and ground-water replenishment occur simultaneously, but the authors have not demonstrated this phase.

The authors have outlined one procedure based on the averages for several years. This is premised on the fact that in a series of years the cycles of precipitation, runoff, and losses must

of necessity balance. Their evidence in Figure 2 shows very close agreement between the averaged and observed yearly cycles. For increased accuracy, the procedure which takes cognizance of the excess or deficiency of stored ground-water at the end of the year seems worth while.

The derivation of the depletion-curve of GRO in Figure 5 is not clear. Presumably, it represents the average of a number of observed hydrograph tails during periods when no surface-runoff existed. A depletion-curve could also be derived by subtracting MEYER'S transpiration values (T) from the mass-curve P-RO-E. This would also give a good smooth curve, but the two depletion-curves would not be in good agreement. MEYER'S derivations of evaporation and transpiration have generally given good results--at any rate, the best now obtainable, but in this case we would naturally expect that the observed depletion-curve would be the more reliable. Viewed in this light, the mass-evaporation plus transpiration of MEYER checks very well. In fact, the whole procedure, as presented by months, has its greatest value in this check of a composite depletion-curve.

The depletion-curve has been applied to the derivation of base-flow under flood-hydrographs. This is erroneous. Ground-water outflow at flood-stages is throttled and is frequently a negative quantity. After the flood-stage recedes, the rate of GRO is greater than that given by the normal depletion-curve until equilibrium takes place. The authors' use of a monthly grouping of rainfall and runoff cancels these effects of flood-peaks on the normal recession-curve.

The authors state that the month-by-month analysis is in the nature of a preliminary report or trial-balance. As such it is a valuable contribution.

Recently several studies have been presented on continuous records of hydrologic phenomena for a year or more. One of these studies was presented by LINSLEY and ACKERMANN [Proc. Amer. Soc. Civ. Eng., June 1941]. They presented the record storm by storm. Your critic sees no reason why the authors could not apply their procedure by storm-units as well as monthly units. Such a study might furnish better working factors than the rather crude empiricisms used by LINSLEY and ACKERMANN.

The quantitative effects of vegetal cover and agricultural works can now be definitely determined by the infiltration-theory for all conditions, storm by storm and season by season. An excellent check on the work would be obtained if the yearly cycle was completed and balanced by the authors' diagram.

DERIVATION OF RIVER-DISCHARGE FROM MEASUREMENTS OF TRIBUTARIES

C. S. Jarvis

For many years various Federal, State, and local agencies have been gaging an ever-increasing number of tributaries and their components, representing considerable percentages of the total drainage-areas above important river-stations, in the course of ascertaining available water-supplies and the extremes of discharge to be expected. From those basic observations, supplemented by further field-study and analysis, comprehensive plans are developed looking toward the most feasible means of conservation, regulation, and utilization of available water-resources, including not only the visible discharge of surface-streams, but also the underground flow and storage-accumulations wherever encountered.

Even when the total gaged-areas have grown to represent the greater portion of the total drainage-area, and a few years of record are available for the lower stations of the main river, there has been some reluctance toward extending the lower-station data on the basis of tributary data and their observed relationships during those years of concurrent records. Nevertheless, occasions have arisen where it became necessary to derive discharge-records synthetically, by using all available data of tributaries and estimating the discharge from the ungaged areas, or checking among separate gagings, as illustrated on pages 42 to 47 of United States Geological Survey Water-Supply Paper 536, dealing with the Kanawha River Basin, West Virginia. Naturally, the relationships developed for the years of concurrent records between the tributary and the lower-river stations will provide important clues, if not the principal guidance for extending the brief or intermittent records. In some instances, the discharge of neighboring streams, together with basic data of rainfall and temperature, may either confirm or revise the previous estimates.

The writer was associate author of a progress-report presented at the Annual Meeting of the Union in May, 1941, entitled "Estimating annual yield from ungaged drainage-basins and effect of

Table 1--Annual mean discharges of the Mississippi River and its principal tributaries, 1889-1938

Year, sub-totals, group-means	Drainage-area in square miles, river, gaging-station							Ratio ungaged to gaged discharge	Departure from mean	1,144,500 square miles, Mississippi, Vicksburg (Mississippi)	1,242,700 square miles, Mississippi and Atchaf., Angola and Simmesport, Louisiana
	203,000 Ohio Metropolis (Illinois)	119,000 Mississippi Keokuk (Iowa)	528,200 Missouri Hermann (Missouri)	27,750 White Clarendon (Arkansas)	157,900 Arkansas Little Rock (Arkansas)	1,033,850 Total from gaged area	119,650 9.7 per cent of area ungaged				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	cfs	cfs	cfs	cfs	cfs	cfs	cfs	pct	pct	cfs	cfs
1889	(200,000)	40,700	(57,000)	(31,000)	(52,000)	380,700	82,300	21.6	+ 0.3	463,000	537,000
1890	(365,000)	54,000	(52,000)	(48,000)	(65,000)	584,000	182,000	31.2	+ 9.9	766,000	815,000
1891	(310,000)	46,300	(65,000)	(35,000)	(45,000)	501,300	94,700	18.9	- 2.4	596,000	689,000
1892	(268,000)	79,200	(80,000)	(45,000)	(70,000)	542,200	160,800	29.7	+ 8.4	703,000	787,000
1893	(260,000)	62,900	(60,000)	(37,000)	(60,000)	479,900	112,100	23.4	+ 2.1	592,000	668,000
Σ	(1,403,000)	283,100	(314,000)	(196,000)	(292,000)	2,488,100	631,900	.....	.....	3,120,000	3,496,000
Σ/5	(280,600)	56,620	(62,800)	(39,200)	(58,400)	497,620	126,380	25.4	+ 4.1	624,000	699,200
1894	(170,000)	48,300	(52,000)	(40,000)	(50,000)	360,300	58,700	16.3	- 5.0	419,000	509,000
1895	(150,000)	30,400	(30,000)	(15,000)	(30,000)	255,400	33,600	13.2	- 8.1	289,000	338,000
1896	(210,000)	47,300	(45,000)	(32,000)	(46,000)	380,300	75,700	19.9	- 1.4	456,000	524,000
1897	(350,000)	68,000	(44,000)	(40,000)	(50,000)	552,000	80,000	14.5	- 6.8	632,000	690,000
1898	(350,000)	42,500	(42,000)	(44,000)	(62,000)	540,500	81,500	15.1	- 6.2	622,000	714,000
Σ	(1,230,000)	236,500	(213,000)	(171,000)	(238,000)	2,088,500	329,500	.....	.....	2,418,000	2,775,000
Σ/5	(246,000)	47,300	(42,600)	(34,200)	(47,600)	417,700	65,900	15.8	- 5.5	483,600	555,000
1899	(318,530)	58,100	(76,640)	(25,000)	(15,750)	494,020	94,980	19.2	- 2.1	589,000	690,000
1900	206,100	57,400	54,070	(22,000)	23,990	363,560	87,440	24.1	+ 2.8	451,000	516,000
1901	231,170	48,500	42,990	(20,000)	15,980	358,640	51,360	14.3	- 7.0	410,000	485,000
1902	245,130	61,900	71,100	(19,000)	30,950	428,080	79,920	18.7	- 2.6	508,000	580,000
1903	282,210	93,900	99,110	(40,000)	43,950	559,170	173,830	31.1	+ 9.8	733,000	826,000
Σ	1,283,140	319,800	343,910	(126,000)	130,620	2,203,470	487,530	.....	.....	2,691,000	3,097,000
Σ/5	256,628	63,960	68,782	(25,200)	26,124	440,694	97,506	22.1	+ 0.8	538,200	619,400
1904	185,090	65,500	93,060	(25,000)	52,600	421,250	103,750	24.6	+ 3.3	525,000	589,000
1905	217,210	82,600	85,060	(28,000)	37,950	450,820	96,180	21.3	0.0	547,000	650,000
1906	259,240	87,100	73,050	(36,000)	44,960	500,350	98,650	19.7	- 1.6	599,000	693,000
1907	324,240	78,900	86,080	(40,000)	39,000	568,220	171,780	30.2	+ 8.9	740,000	826,000
1908	291,210	71,500	94,080	(33,000)	83,000	572,790	144,210	25.2	+ 3.9	717,000	815,000
Σ	1,276,990	385,600	431,330	(162,000)	257,510	2,513,430	614,570	.....	.....	3,128,000	3,573,000
Σ/5	255,398	77,120	86,266	(32,400)	51,502	502,686	122,914	24.5	+ 3.2	625,600	714,600

Table 1--Annual mean discharges of the Mississippi River and its principal tributaries, 1889-1938--Continued

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	cfs	cfs	cfs	cfs	cfs	cfs	cfs	pct	pct	cfs	cfs
1909	278,150	73,400	95,110	(26,000)	26,960	499,620	145,380	29.1	+ 7.8	645,000	713,000
1910	236,120	41,500	62,070	(23,000)	15,980	378,770	95,230	25.1	+ 3.8	474,000	539,000
1911	278,200	50,500	42,990	(24,000)	15,980	406,670	53,330	13.1	- 8.2	460,000	526,000
1912	337,000	62,200	76,030	(35,000)	33,970	544,200	113,800	20.9	- 0.4	658,000	759,000
1913	327,240	53,300	53,040	(31,000)	22,980	487,560	130,440	26.8	+ 5.5	618,000	698,000
Σ	1,451,710	281,000	329,240	(139,000)	115,870	2,316,820	538,180	.....	.....	2,855,000	3,235,000
Σ/5	290,342	56,200	65,848	(27,800)	23,174	463,364	107,636	23.2	+ 1.9	571,000	647,000
1914	190,190	50,100	52,020	(25,000)	18,950	336,260	40,740	12.1	- 9.2	377,000	458,000
1915	272,150	75,500	134,100	(29,000)	68,990	579,740	96,260	16.6	- 4.7	676,000	798,000
1916	315,230	82,300	98,090	(42,000)	54,020	591,640	131,360	22.2	+ 0.9	723,000	816,000
1917	319,130	59,200	82,080	(23,000)	13,000	496,410	72,590	14.6	- 6.7	569,000	643,000
1918	244,230	52,300	62,070	(14,000)	20,010	392,610	20,390	5.2	-16.1	413,000	480,000
Σ	1,340,930	319,400	428,360	(133,000)	174,970	2,396,660	361,340	.....	.....	2,758,000	3,195,000
Σ/5	268,186	63,880	85,672	(26,600)	34,994	479,332	72,268	15.1	- 6.2	551,600	639,000
1919	324,240	71,000	70,080	(38,000)	33,970	537,290	111,710	20.8	- 0.5	649,000	740,000
1920	314,330	66,100	89,160	(35,000)	34,980	539,570	165,430	30.7	+ 9.4	705,000	807,000
1921	257,140	48,100	74,080	(40,000)	37,950	457,270	87,730	19.2	- 2.1	545,000	637,000
1922	303,970	56,400	85,060	(40,000)	41,980	527,410	94,590	17.9	- 3.4	622,000	719,000
1923	293,160	39,300	76,130	(50,000)	71,970	530,560	81,440	15.3	- 6.0	612,000	708,000
Σ	1,492,840	280,900	394,510	(203,000)	220,850	2,592,100	540,900	.....	.....	3,133,000	3,611,000
Σ/5	298,568	56,180	78,902	(40,600)	44,170	518,420	108,180	20.9	- 0.4	626,600	722,200
1924	295,270	52,700	81,050	(28,000)	34,980	492,000	95,000	19.3	- 2.0	587,000	649,000
1925	188,090	37,000	76,130[a]	(22,000)	17,990	341,210	35,790	10.5	-10.8	377,000	436,000
1926	276,200	56,000	82,080	(24,000)	40,970	479,250	54,750	11.4	- 9.9	534,000	590,000
1927	411,300	69,400	138,300	(74,000)	97,970	790,970	114,030	14.4	- 6.9	905,000	1,116,000
1928	292,260	71,400	96,140	52,750	49,990	562,540	133,460	23.7	+ 2.4	696,000	742,000
Σ	1,463,120	286,500	473,700	(200,750)	241,900	2,665,970	433,030	.....	.....	3,099,000	3,533,000
Σ/5	292,622	57,300	94,740	(40,150)	48,380	533,194	86,606	16.2	- 5.1	619,800	706,600
1929	341,350	67,800	103,010	51,420	60,020	623,600	145,400	23.3	+ 2.0	769,000	820,000
1930	176,080	39,200	55,100	28,990	32,960	332,330	116,670	35.1	+13.8	449,000	500,000
1931	120,000	31,800	46,070	20,430	23,990	242,290	75,010	31.0	+ 9.7	317,300[b]	348,000
1932	(275,000)	44,100	(65,000)	23,210	(30,000)	437,310	120,790	27.6	+ 6.3	558,100	630,000
1933	306,600	41,160	51,600	32,860	35,300	467,520	137,780	29.5	+ 8.2	605,300	640,000
Σ	1,219,030	224,060	320,780	156,910	182,270	2,103,050	595,650	.....	.....	2,698,700	2,938,000
Σ/5	243,806	44,812	64,156	31,382	36,454	420,610	119,130	28.3	+ 7.0	539,740	587,600

[a] This item should be reduced 34.3 per cent to 50,000 cfs [see p. 532].

[b] Only thoroughly official quantities U. S. Geol. Surv. in Columns (11) and (12) are those following 1930.

Table 1--Annual mean discharges of the Mississippi River and its principal tributaries, 1889-1938--Concluded

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	cfs	cfs	cfs	cfs	cfs	cfs	cfs	pct	pct	cfs	cfs
1934	155,300	27,380	32,570	17,120	20,090	252,460	70,540	27.9	+ 6.6	323,000	352,000
1935	291,200	55,350	79,190	44,400	67,080	537,220	139,380	25.9	+ 4.6	676,600	780,000
1936	231,800	46,040	39,820	11,560	14,510	343,730	63,970	18.6	- 2.7	407,700	441,000
1937	340,900	48,680	55,440	(32,000)	31,260	508,280	116,220	22.9	+ 1.6	624,500	690,000
1938	251,200	74,540	60,340	(38,000)	44,680	468,760	102,240	21.8	+ 0.5	571,000	660,000
Σ/5	1,270,400	251,980	267,360	143,080	177,620	2,110,450	492,350	.....	.....	2,802,800	2,923,000
Σ/5	254,080	50,398	53,472	28,616	35,524	422,090	98,470	23.3	+ 2.0	520,560	584,600
Grand total	13,431,160	2,868,850	3,516,190	1,630,740	2,031,610	23,478,550	5,024,950	1,064.7	264.7	28,503,500	32,376,000
50-year mean	268,623	57,377	70,324	32,615	40,632	469,571	100,499	21.3	5.29	570,070	647,520

Note: Parentheses enclose derived, estimated, or unofficial quantities. Many official data for 1900 to 1931 were derived from Comprehensive report on reservoirs in Mississippi River Basin by Corps of Engineers, U. S. Army [H.D. 259, 74th Congress, 1st Sess., Tables 2 and 13, 1935]. For 1939 and 1940, values are 541,600 and 350,200 for Column (11) and 603,000 and 415,000 for Column (12).

land-use treatment on surface-runoff." Therein it was shown that the mean annual discharge of the Mississippi River at Vicksburg, Mississippi, as independently derived from voluminous records and hydrographs, could likewise be estimated from sample tributary or headwaters records with fair agreement, in general. Specifically, the maximum divergence between the two sets of values, expressed as percentage-departures from the series utilizing the Vicksburg hydrographs and related records, was ordinarily less than half of the percentage representing ungaged area, while the mean departure was more nearly one-fourth to one-seventh of the ungaged percentage. Thus, with only 9.6 per cent gaged, leaving 90.4 per cent as ungaged, the maximum and mean departures for a ten-year record proved to be 30.2 and 12.1 per cent, respectively, for water-years, or 25.5 and 10.9 per cent for calendar years. Similarly, with 83.7 per cent of the area ungaged, the 65-year record developed maximum and mean departures of 33.7 and 12.1 per cent, respectively, for water-years, and 42.3 and 11.6 per cent for calendar years. By way of contrast, with 90.2 per cent of the area gaged, leaving only 9.8 per cent ungaged, (which yielded 18.9 per cent of the total discharge at Vicksburg) a 12-year record developed maximum and mean departures of only 4.5 and 2.5 per cent, respectively [Trans. Amer. Geophys. Union, 1941, p. 886, item 12 of Table 5].

Table 1 presented herewith represents practically an extension of the 12-year record last mentioned, but with the records from Clarendon, Arkansas, of the White River discharge substituted for those at De Valls Bluff, thus changing the gaged area percentage to 90.3. Most of the additional 38 years of added record are derivable from Tables 2 and 13, House Document 259, 74th Congress, 1st Session, "Comprehensive report on reservoirs in Mississippi River Basin," by the Corps of Engineers, United States Army, 1935, but also include some derived or unofficial quantities--those enclosed in parentheses.

Even among the discharge-data officially released from time to time by various agencies, such as along the Mississippi River and its larger tributaries, considerable divergence may be expected. For the earlier years, particularly, the standards of accuracy and reliability were not so well established as for those of the latest 12 years. It is, therefore, not surprising that the maximum and mean departures observed for the 50-year record are considerably higher than for the latest 12-year period, or -16.1 and ± 5.3 per cent, respectively; or, reduced to comparable basis of reckoning, using the ratio of total annual discharge at Vicksburg to the gaged discharge instead of comparing the ungaged with the gaged discharge, these percentages become -13.3 and ± 4.4. Adopting the nomenclature of last year's paper, above referred to, it is readily seen that the difference between the two ratios (U/G) and [(U + G)/G] is exactly 1.00; that is, the ratio of

ungaged to gaged discharge is 1.00 less than the ratio of total discharge to gaged discharge.

Inasmuch as the quantity being sought is the total discharge at the lower-river station, rather than the ungaged portion thereof, it seems best to favor the larger ratio, even though they are readily transformable from one to the other.

Among the concepts submitted for investigation during the quest for methods and means for interpreting tributary runoff-records in terms of the main river-discharge is that of weighting-factors. For example, among the few available records of 50 or 60 years' standing, the best geographic distribution is provided by the Missouri River at Fort Benton (Montana), the Mississippi River at Keokuk (Iowa), the Kanawha River at Kanawha Falls (West Virginia), the Cumberland River at Nashville (Tennessee), and the Tennessee River at Chattanooga (Tennessee), controlling a total gaged area equal to 16.3 per cent of the drainage-basin above Vicksburg (Mississippi), and yielding 24.6 per cent of the total at Vicksburg. Should these various sample areas have equal weight, in spite of their unequal size and runoff-yield per square mile? Perhaps the solution of as many simultaneous algebraic equations as there are unknown weighting-factors may shed some

Table 2--Derived values of weighting factors for designated stations within the Mississippi River Basin

Drainage-area in square miles, river, gaging-station, weighting factor						Test-period	
24,600, Missouri, Fort Benton (Montana), u	88,600[a] or 119,000, Mississippi, Le Claire[a] or Keokuk (Iowa), v	1,357[d] or 8,367, Greenbrier,[d] Alderson, or Kanawha, Kanawha Falls (W. Va.), w	12,860, Cumberland, Nashville (Tennessee), x	21,390, Tennessee, Chattanooga (Tennessee), y	3,180, Gasconade, Rich Fountain (Missouri), z	Years	Serial No.
- 39.7074	11.7026	134.4694	-37.3408	- 22.8086	.....	1892-96[b]	1
-165.4955	18.8199	609.8722	.....	-182.9213	.....	1892-95[b]	2
-156.0[c]	18.35	580.0	.....	-174.6	.....	1892-95[b]	3
.....	6.8917	11.6667	.....	.....	.....	1892-93	4
.....	8.1266	10.5935	.....	.....	.....	1894-95	5
- 26.9696	3.4191	19.0314	23.8306	- 7.4450	.....	1934-38[b]	6
- 23.7704	3.1095	- 26.6305	.....	16.3435	92.9170	1934-38[b]	7
.....[c]	.....	17.55	.....	.....	147.8	1936-37[b]	8
.....[c]	.....	- 22.35	.....	.....	293.0	1937-38[b]	9
.....	1.3340	16.4703	.....	5.7096	.....	1878-80	10
21.3425	2.7593	26.9060	.....	- 3.1346	.....	1882-85	11
.....	23.8696	- 60.0000	.....	.....	.....	1886-87	12
.....	3.8837[a]	.....	.....	11.0027	.....	1876-77	13
.....	2.3948[a]	.....	.....	15.9249	.....	1879-80	14
.....	11.6675[a]	.....	.....	- 1.9182	.....	1882-83	15
.....[c]	9.4515[a]	.....	.....	1.6870	.....	1885-86	16
.....	.....	0.296401	.....	.....	204.3807	1939-40[b]	17

.....	157,900, Arkansas, Little Rock (Arkansas), v	8,367, Kanawha, Kanawha Falls (W. Virginia), w	23,800, White, De Valls Bluff (Arkansas), x	.....	3,180, Gasconade Rich Fountain (Missouri), z	Test-period	
						Years	Serial No.
.....	3.3956[e]	18.9086[e]	-16.6415[e]	.....	322.4417[e]	1936-39[b]	18
.....	- 2.6885[f]	18.9412[f]	-18.7450[f]	.....	342.6477[f]	1936-39[b]	18A
.....	1.730,56[g]	18.5344[g]	-10.5184[g]	.....	279.0549[g]	1936-39[b]	18B
.....	.....	.....[dg]	10.5687[g]	.....	118.7696[g]	1938-39[b]	18C
.....	.....	47.4144	.....	.....	193.8274[g]	1938-39[b]	18D

[a]Le Claire records used in place of those for Keokuk, Iowa.

[b]Water-years, October 1 to September 30, the later year being listed.

[c]Slide-rule calculations only.

[d]Using data from the Greenbrier tributary at Alderson, West Virginia, in place of those for Kanawha River.

[e]Lower station, Vicksburg, Mississippi, using official data for Little Rock, Kanawha Falls, De Valls Bluff, and Rich Fountain.

[f]Solution as for serial No. 18 but using Kanawha Falls data of 1939 which are in error by +8 per cent, that is, are 8 per cent too great.

[g]Lower station, Angola, Louisiana.

Table 3--Derived values of weighting factors for major tributaries of the Mississippi River System and of the Ohio River System

Drainage-area in square miles, river, gaging-station, weighting factor						Test-period	
528,200, Missouri, Hermann (Missouri), u	119,000, Mississippi, Keokuk (Iowa), v	203,000, Ohio, Metropolis (Illinois), w	25,750 or 23,800,[a] White, Clarendon or De Valls Bluff[a] (Ark.), x	157,900, Arkansas, Little Rock (Arkansas), y	51,500, Red, Garland (Arkansas), z	Years	Serial No.
Mississippi-Atchafalaya rivers at Red River Landing and Simmesport, Louisiana, drainage-area, 1,242,700 square miles							
2.764,051	0.724,094	1.051,250	3.800,112	0.688,561	.....	1934-38	19
3.223,343	0.282,345	0.926,350	6.209,554	- 0.541,716	.....	1934-38[b]	20
2.042,846	- 2.348,207	1.776,129	-5.238,200[a]	0.449,261	13.287,423	1933-38[c]	21
3.462,503	- 0.319,167	1.014,236	4.864,623[a]	- 0.392,408	3.315,137	1935-40[c]	22
-0.540,756	0.534,084	1.527,006	.....	5.189,840	0.376,413	1934-38[c]	23
-0.669,544[e]	0.602,864[e]	1.533,808[e]	.....	5.420,329[e]	.....	1935-38[c]	24
-0.670,343[f]	0.605,899[f]	1.533,165[f]	.....	5.421,724[f]	.....	1935-38[c]	24A
Mississippi River at Vicksburg, Mississippi, drainage-area, 1,144,500 square miles							
-8.890,448	13.809,793	0.756,548	-6.522,136	13.754,439	.....	1927-31	25
0.606,386	2.455,054	1.582,193	.....	.....	.....	1927-29	26
4.298,608	- 1.724,672	1.482,328	.....	.....	.....	1933-35	27
.....	2.511,146	1.637,119	.....	.....	.....	1933-34	28
2.548,392	.....	1.545,347	.....	.....	.....	1933-34	29
3.916,805	.....	1.258,338	.....	.....	.....	1934-35	30
12.283,804	- 3.324,730	0.308,997	.....	.....	.....	1936-38	31
.....	- 2.865,939	1.422,663	.....	.....	.....	1937-38	32
.....	- 1.309,014	2.018,842	.....	.....	.....	1936-37	33
5.686,730	.....	0.907,098	.....	.....	.....	1937-38	34

Ohio River at Metropolis, Illinois, drainage-area, 203,000 square miles						
16,000, Cumberland, Clarksville (Tennessee), u	6,310, Kentucky, Lockport (Kentucky), v	3,640, Miami, Hamilton (Ohio), w	3,850, Scioto, Chillicothe (Ohio), x	7,411, Muskingum, McConnelsville (Ohio), y	Test-period: Years	Test-period: Serial No.
1.615,377	11.279,73	19.542,55	-19.304,04	15.667,98	1935-39[c]	35
3.32	7.13	.....	.....	14.60	1935-37[dc]	36
20.08	-23.22	.....	.....	.....	1938-39[dc]	37
6.95	.....	.....	.....	13.82	1938-39[dc]	38
6.44	.....	.....	.....	14.66	1935-36[dc]	39
38,510, Tennessee, Johnsonville (Tennessee), u	28,600, Wabash, Mt. Carmel (Illinois), v	8,367, Kanawha, Kanawha Falls (W. Virginia), w	1,304, Tygart, Fetterman (W. Virginia), x	1,640, Allegheny, Red House (New York), y	Test-period: Years	Test-period: Serial No.
5.001,96	2.881,28	18.161,82	-166.161,90	40.784,23	1935-39[c]	40
0.854,180	4.962,72	7.359,34	.....	.....	1935-37[c]	41
2.777,78	3.797,29	.....	.....	.....	1936-37[c]	42
3.690	1.544	.....	.....	.....	1938-39[dc]	43
3.8835	.....	3.2858	.....	.....	1938-39[c]	44

[a]Records of White River at De Valls Bluff substituted for those at Clarendon, Arkansas.

[b]Discharge for the year 1936 at Lower River stations was too small by 21,000 cfs or five per cent.

[c]Water-years, October 1 to September 30, the later year being listed as the year of record.

[d]Slide-rule calculations only. [e]Approximate. [f]Revised.

light on the problem. Listing the five tributary or sample areas in the same order as above given, and supplying the necessary weighting-factors, the summation must equal the discharge for the year at Vicksburg, Mississippi. For the calendar year 1938 the equation becomes

$$6{,}306\,v + 74{,}540\,w + 10{,}677\,x + 22{,}500\,y + 33{,}980\,z = 571{,}100$$

or for the water-year (October 1 to September 30)

$$6{,}010\,v + 65{,}520\,w + 13{,}170\,x + 29{,}420\,y + 35{,}720\,z = 567{,}300$$

Using the discharge-data of the four water-years immediately preceding in similar equations, then solving for the various unknowns, resulted in the set of values as listed for test-period 6 in Table 2, ranging from -26.97 to +23.83. While these values satisfied the five original equations, they were not so satisfactory for the two separate decades immediately preceding the five-year test-period, as shown under test-period 6 of Table 4, along with the very acceptable tests of [(U + G)/G].

As a part of this investigation, a sixth term was added to the left-hand member to represent the total ungaged discharge, with its weighting-factor "u". This called for the use of a sixth equation. The first solutions, by slide-rule, brought such results as the following, all satisfying the original equations within a minor fraction of one per cent, and likewise checking on the remaining 59 years of available record within two per cent, with a mean departure of ± 0.6 per cent.

u	v	w	x	y	z
0.9965	0.8021	1.0433	2.1893	0.5918	0.7946

Such arrays of values, repeated with some variations for different test-periods, seemed to warrant the conclusion that the Kanawha River deserved heavier weighting or representation, and that the data for the Cumberland and Tennessee rivers were somewhat overlapping, thus requiring weighting-factors less than unity. These theories were all dispelled, however, when the small errors associated with slide-rule or other calculations were eliminated, for the weighting-factors reduce to 1.0000 in all cases where the discharge of the ungaged area appears as a term in the equation. It seems worth some consideration in view of the fact that such divergent arrays of weighting-factors applied to their associated yearly discharges, year by year, check so closely with the observed discharge at the lower-river station. It provides a mild precedent for what follows with the weighting-factors for gaged tributaries running up to such values as -165.5, +18.82, +609.9, and -182.9, as shown to additional decimals under test-period 2 in Table 2. The occurrence of negative values seems to indicate a sort of reciprocal relationship, whereby a heavy contribution from the Missouri River would be associated with a deficient contribution from the Ohio River, to a limited extent; so that the algebraic difference instead of their summation seems to govern the lower-station discharge. For test-period 40, in Tables 3 and 4, only the Tygart River has a negative weighting-value, namely, -166.16, while the other four tributaries have factors ranging from 2.88 to 40.78.

Inasmuch as the officially published data underlying Table 1 afford a fair approximation, if not actual records of discharge for the major tributaries, a new equation was set up in which the Missouri River at Hermann, Missouri, takes the place of the Fort Benton data. Likewise, the Ohio River at Metropolis (Illinois) takes the place of the Kanawha River, and the Arkansas River at Little Rock (Arkansas), together with the White River at Clarendon (Arkansas) take the places formerly occupied by the Cumberland and Tennessee River records of discharge at Nashville and Chattanooga, respectively. With the Mississippi River at Keokuk (Iowa) retaining its original position as the second term in each equation of the new series, the total gaged area amounts to 90.3 per cent, leaving only 9.7 per cent of the area ungaged, yet producing nearly 19 per cent of the discharge at Vicksburg.

Results obtained from solutions of the new series of simultaneous equations are placed under new headings of Table 3, yet retaining the original sequence of test-period numbers, beginning with No. 19.

The groups of weighting-factors obtained for different combinations of station-records and test-periods are shown in Tables 2 and 3. The actual behavior of these weighting-factors under test, when applied to other years, is shown in Table 4, both for the weighting-factors as applied to sampling, and for the ratios of total discharge at the lower-river station to the gaged discharges of tributaries or headwaters. Therein it is shown that either of the methods may be used to extend the horizons of hydrologic data with fair assurance. Each method has its advantages and its defects. Neither one has the advantage throughout the various tests--they seem to alternate. The simplest procedure is associated with the direct comparisons of total discharge at the lower-river station with the sum of the contributions from gaged areas. The weighting-factors provide an alternate method of approach, with some advantages accruing at times to make the more tedious approach worth while.

Several tests involving both of the methods compared in Table 4 disclosed considerable irregularity for the year 1901. The term responsible for most of the overplus was the disproportionately high discharge of the Kanawha River at Kanawha Falls for the year 1901. Instead of attaining a value from 40 to 80 per cent of that recorded for the neighboring Cumberland River at Nashville, the mean annual discharge of the Kanawha River for 1901 purports to be nearly equal,

Table 4--Comparison of methods for deriving river-

River-discharge derived from tributary records and weighting factors

Test No.	Test-period for solution simultaneous linear equations and gaged discharges		Checking period for comparing discharges derived for years outside the test-period		Departures of computed quantities from recorded discharges at lower stations				
					Test-period		Checking period		
	No. years	Period	No. years	Period	Maximum	Mean	Maximum	Mean absolute	Mean
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
					pct	pct	pct	pct	pct
1	5	1892-1896	16	1881-1891, 1897-1901	+0.2	±0.1	+ 29.4[a]	±16.8	+ 4.8
			21	1881-1901	.....	.....	+ 29.4[a]	±12.8	+ 3.9
			65	1875-1939	.....	.....	.....	±22.3	-11.4
2	4	1892-1895	5	1882-1886	-0.07	±0.03	+ 46.8	±32.4	-10.6
3	4	1892-1895	5	1882-1886	-1.2	±0.7	+ 42.4	±31.2	- 9.5
4	2	1892-1893	5	1894-1898	0.00	0.00	+ 36.6	±20.2	+ 7.0
			20	1886-1905	0.00	0.00	+ 37.1[a]	±14.6	+ 8.6
			65	1875-1939	0.00	0.00	.....	.....	+ 2.4
5	2	1894-1895	5	1885-1889	0.00	0.00	- 18.4	± 7.6	- 6.0
			20	1886-1905	0.00	0.00	- 39.6	±16.7	-15.8
			65	1875-1939	0.00	0.00	.....	.....	-20.6
6	5	1934-1938	20	1914-1933	-0.19	±0.06	- 54.0	±24.1	-23.1
			65	1875-1939	.....	.....	.....	.....	-22.8
7	5	1934-1938	12	1923-33,39	0.00	0.00	- 23.9	±11.9	- 6.2
			65	1875-1939	.....	.....	- 23.9	± 9.6	+ 2.2
8	2	1936-1937	17	1923-1939	0.00	0.00	+ 58.1	±17.7	+10.6
			65	1875-1939	.....	.....	.....	.....	+30.3
9	2	1937-1938	17	1923-1939	0.00	0.00	-100.0	±33.6	+ 1.3
			65	1875-1939	.....	.....	.....	.....	+26.8
10	3	1878-1880	10	1881-1890	-0.14	±0.08	- 25.3	±11.4	- 5.9
			20	1891-1910	.....	.....	+ 46.6	±15.6	- 6.5
			65	1875-1939	.....	.....	.....	.....	- 9.8
11	4	1882-1885	22	1880-1901	-0.03	±0.02	+ 35.4	±18.8	+11.4
			65	1875-1939	.....	.....	.....	.....	+ 1.8
12	2	1886-1887	20	1907-1926	0.00	0.00	+ 50.8	±24.5	+11.4
			65	1875-1939	.....	.....	.....	.....	+17.2
13	2	1876-1877	15	1925-1939	0.00	0.00	+ 39.8	±13.7	- 3.9
			65	1875-1939	.....	.....	.....	.....	+ 5.8
14	2	1879-1880	15	1925-1939	0.00	0.00	+ 74.3	±24.3	+17.0
15	2	1882-1883	15	1925-1939	0.00	0.00	- 54.8	±30.5	+32.1
16	2	1885-1886	10	1875-1884	.....	.....	.....	.....	+ 5.2
			15	1925-1939	0.00	0.00	- 42.2	±23.8	-24.5
			65	1875-1939	.....	.....	.....	.....	-10.2
17	2	1939-1940	19	1922-1940	0.00	0.00	+ 46.3	±21.1	+ 3.0
18	4	1936-1939	20	1921-1940	0.00	0.00	- 65.0	±26.1	+ 0.8
18A	4	1936-1939	20	1921-1940	0.00	0.00	- 64.8	±28.5	+ 0.8
18B	4	1936-1939	20	1921-1940	-0.08	±0.07	+ 51.8	±18.3	+ 2.7
18C	2	1938-1939	20	1921-1940	0.00	0.00	- 41.1	±13.5	- 0.7
18D	2	1938-1939	20	1921-1940	0.00	0.00	+ 50.7	±15.5	+ 2.3
19	5	1934-1938	50	1889-1938	0.00	0.00	+ 19.0	± 5.1	+ 3.9
20	5	1934-1938	50	1889-1938	0.00	0.00	+ 18.8	± 6.1	+ 4.3
21	6	1933-1938	13	1928-1940	0.00	0.00	- 20.1	± 4.9	- 2.6
22	6	1935-1940	13	1928-1940	0.00	0.00	+ 18.8	± 4.4	+ 4.0
			50	1889-1938	.....	.....	.....	.....	+ 4.9
23	5	1934-1938	15	1926-1940	0.00	0.00	- 9.3	± 2.6	- 2.2
			50	1889-1938	.....	.....	.....	.....	- 3.9
24	4	1935-1938	15	1926-1940	0.00	0.00	- 23.8	± 4.0	- 2.3
			50	1889-1938	.....	.....	.....	.....	- 4.0
25	5	1927-1931	21	1919-1939	-0.07	±0.02	+ 83.8	±19.3	+ 5.1
			51	1889-1939	.....	.....	.....	.....	+25.5
26	3	1927-1929	21	1919-1939	0.00	0.00	+ 23.6	± 7.6	+ 5.7
			51	1889-1939	.....	.....	+ 33.7	± 9.1	+ 6.7
27	3	1933-1935	21	1919-1939	0.00	0.00	+ 43.8	± 9.7	+ 9.1
			51	1889-1939	.....	.....	.....	.....	+ 7.5
28	2	1933-1934	21	1919-1939	0.00	0.00	+ 21.4	± 6.6	+ 1.2
			51	1889-1939	.....	.....	.....	.....	+ 2.4
29	2	1933-1934	21	1919-1939	0.00	0.00	+ 27.9	± 7.3	+ 5.9

discharges from records of tributaries

Drainage-area comparisons		River-discharge from tributary records and comparison yields gaged areas (G), ungaged areas (U), and total area (U + G)					
		Ratios (U + G)/G or lower river-discharge to gaged discharge		Departures of derived data from recorded discharges at lower river stations			Remarks (see footnotes)
Gaged	R [see notes]	Test-period	Checking period	Max. yearly	Mean absolute	Mean	
(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
pct				pct	pct	pct	
16.3	6.15	3.791	3.7865[a]	+38.1[a]	±10.8	- 0.1	b
16.3	6.15	3.791	3.7875[a]	+38.1[a]	±14.4	- 0.1	b
16.3	6.15	3.791	4.062 [a]	+40.6[a]	±10.0	+ 7.2	b
15.1	6.60	4.320	4.140	-15.5	± 7.5	- 4.2	b
15.1	6.60	4.320	4.140	-15.5	± 7.5	- 4.2	b,c
11.1	8.99	7.725	7.780	+37.3	±14.9	+ 0.7	b
11.1	8.99	7.725	7.444	+37.3[a]	±12.5	- 3.6	b
11.1	8.99	7.725	7.750	.....	.....	+ 0.3	b
11.1	8.99	6.385	6.563	+18.8	±12.2	+ 2.8	b
11.1	8.99	6.385	7.444	+66.0	±21.5	+16.6	b
11.1	8.99	6.385	7.746	.....	.....	+21.3	b
16.3	6.13	4.218	4.362	+37.0	±10.2	+ 3.4	b
.....	.....	4.218	4.057	+37.0	±11.8	- 3.6	b
15.4	6.48	5.046	5.404	+25.8	±10.9	+ 7.1	b
15.4	6.48	5.046	4.617	-36.0	±13.6	- 8.5	b,d
1.0	99.12	35.52	38.98	+41.0	±15.8	+ 9.8	b,d
1.0	99.12	35.52	34.40	.....	.....	- 3.2	b,d
1.0	99.12	38.25	38.98	-31.0	±14.5	+ 1.9	b,d,e
1.0	99.12	38.25	34.40	.....	.....	-10.1	b,d,e
13.0	7.70	4.580	4.605	+40.2	± 6.0	+ 0.5	f
13.0	7.70	4.580	4.941	+47.1	±15.7	+ 7.9	f,g
.....	.....	4.580	5.095	.....	.....	+11.2	f,g
15.1	6.60	4.385	4.384	+36.9	±10.8	0.0	f,g
.....	.....	4.385	4.740	.....	.....	+ 8.1	f,g
11.1	9.00	7.031	8.253	+60.2	±21.0	+17.4	b
.....	.....	7.031	7.750	.....	.....	+10.2	b
9.6	10.41	7.136	7.589	+44.3	±14.7	+ 6.3	f
.....	.....	7.136	6.673	.....	.....	- 6.5	f
9.6	10.41	5.359	7.589	+92.1	±44.9	+41.5	f
9.6	10.41	6.068	7.589	+69.7	±26.4	+25.1	f
.....	.....	.....	5.939	.....	.....	+ 0.5	f
9.6	10.41	5.936	7.589	+73.5	±38.9	+27.8	f
.....	.....	.....	6.673	.....	.....	+12.4	f
1.0	99.12	36.595	38.465	+36.9	±17.4	+ 5.1	b
16.9	5.92	6.071	6.890	+69.5	±22.2	+13.5	b
16.9	5.92	6.058	6.887	+69.8	±22.3	+13.7	b,h
16.9	5.92	6.742	7.710	+61.4	±20.6	+14.4	b,i
2.2	46.06	20.230	20.807	+87.8	±15.4	+ 2.9	b,i
0.4	273.9	134.031	128.985	+30.5	±13.6	- 3.8	b,i
83.2	1.20	1.385	1.359	-12.8	± 4.0	- 1.9	f,i
83.2	1.20	1.375	1.373	-12.2	± 4.0	- 0.1	f,i,j
87.2	1.15	1.242	1.322	+13.2	± 6.5	+ 6.4	b,i
87.2	1.15	1.340	1.322	- 8.5	± 2.6	- 1.3	b,i
.....	.....	1.340	1.337	.....	.....	- 0.2	b,i
85.3	1.17	1.413	1.408	-10.7	± 3.3	- 0.4	b,i
.....	.....	1.413	1.418	.....	.....	+ 0.4	b,i
81.1	1.23	1.494	1.466	-13.7	± 4.4	- 2.0	b,i
.....	.....	1.494	1.476	.....	.....	- 1.2	b,i
90.4	1.11	1.229	1.211	-10.1	± 4.4	- 1.5	f,h
.....	.....	1.229	1.225	-14.4	± 4.5	- 0.3	f,h
74.3	1.35	1.490	1.439	-16.1	± 5.1	- 3.4	f,h,k
.....	.....	1.490	1.438	-22.6	± 6.4	- 3.5	f,h,k
74.3	1.35	1.543	1.439	-18.6	± 6.9	- 6.7	f,h,k
.....	.....	1.543	1.438	-25.3	± 8.0	- 6.9	f,h,k
28.1	3.55	1.750	1.759	+19.4	± 7.0	+ .0.5	f,h,k
.....	.....	1.750	1.747	-20.3	± 8.2	- 0.2	f,h,k
63.9	1.57	1.700	1.657	-15.9	± 6.4	- 2.5	f,h,k

Table 4--Comparison of methods for deriving river-

River-discharge derived from tributary records and weighting factors

Test No.	Test-period for solution simultaneous linear equations and gaged discharges		Checking period for comparing discharges derived for years outside the test-period		Departures of computed quantities from recorded discharges at lower stations				
					Test-period		Checking period		
	No. years	Period	No. years	Period	Maximum	Mean	Maximum	Mean absolute	Mean
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
					pct	pct	pct	pct	pct
30	2	1934-1935	21	1919-1939	0.00	0.00	+ 41.7	± 9.5	+ 9.3
31	3	1936-1938	21	1919-1939	-0.01	0.00	+130.8	±38.0	+37.8
			51	1889-1939	.....	.....	.....	.....	+32.9
32	2	1937-1938	21	1919-1939	0.00	0.00	- 19.2	± 8.1	- 6.0
			51	1889-1939	.....	.....	.....	.....	- 4.2
33	2	1936-1937	21	1919-1939	0.00	0.00	- 36.8	±16.1	-15.4
34	2	1937-1938	21	1919-1939	0.00	0.00	+ 60.0	±15.4	+14.8
35	5	1935-1939	12	1928-1939	0.00	0.00	- 33.3	±12.6	-11.7
			41	1899-1939	.....	.....	.....	.....	-16.0
36	3	1935-1937	12	1928-1939	±0.2	±0.17	- 25.9	±10.0	- 9.4
			41	1899-1939	.....	.....	.....	.....	- 5.5
37	2	1938-1939	12	1928-1939	+0.3	+0.2	+ 65.0	±20.5	+17.1
38	2	1938-1939	12	1928-1939	0.00	0.00	+ 14.5	± 4.9	+ 1.1
39	2	1935-1936	12	1928-1939	-0.09	±0.06	- 14.8	± 4.7	- 1.6
40	5	1935-1939	13	1927-1939	-0.06	±0.03	+ 43.8	±10.6	+ 7.7
			41	1899-1939	.....	.....	.....	.....	+ 9.7
41	3	1935-1937	13	1927-1939	+0.3	+0.2	+ 19.2	± 5.8	+ 0.9
			41	1899-1939	.....	.....	.....	.....	+ 2.3
42	2	1936-1937	13	1927-1939	0.00	0.00	+ 11.4	± 4.7	+ 2.8
			41	1899-1939	.....	.....	.....	.....	+ 2.5
43	2	1938-1939	13	1927-1939	-0.2	-0.1	+ 12.0	± 5.5	+ 1.2
			41	1899-1939	.....	.....	.....	.....	+ 2.3
44	2	1938-1939	13	1927-1939	0.00	0.00	+ 29.1	±10.4	+ 3.8
			41	1899-1939	.....	.....	± 38.5	±15.0	± 9.0

[a]Revised data for the 3 years 1889-1890 and 1901. [b]Water years, October 1 to September 30 of the following calendar year. [c]Slide-rule computations only. [d]Includes estimated data. [e]Kanawha - Gasconade records. [f]Calendar years. [g]Revised Kanawha data 1901. [h]Vicksburg data. [i]Angola, Louisiana, data. [j]Basic data for 1936 off -5 per cent. [k]Partly estimated. [l]Ohio River System. [m]Absolute means regardless of sign.

GENERAL NOTES: R = ratio of total drainage-area to gaged area.

Yearly or other periodic discharges as recorded, derived, or partially estimated for gaging-stations on tributaries or head-waters, each multiplied by appropriate "weighting factors," or by ratios comparing either gaged drainage-areas or their respective

and thus invites reconsideration with a view toward revision downward. For only one year, 1878, of estimated discharge for the Cumberland, and for no other year than 1901 of the 44 years of concurrent record, has the Kanawha either equaled or exceeded that of the Cumberland--it is ordinarily less than 70 per cent. Examination of the rainfall-records at 17 stations in or near the Kanawha Basin disclosed that the mean rainfall-excess for the year 1901 was only 16 per cent, in contrast with the excess of 60 per cent as published for the discharge of the Kanawha. By reducing the discharge-quantity to conform with the mean rainfall-excess of 16 per cent, it was found that various tests by both of the methods compared in Table 4, and by other means, confirm the need for such corrections. Likewise for 1889 and 1890 similar revisions were required, amounting to -27 per cent and +26 per cent, respectively, of the 65-year mean discharge. These are the corrections referred to in the marginal note of Item 1, Table 4.

The need for future study and revision of the data from the Kanawha River, due to lack of early gagings and control, is indicated on page 43 of the United States Geological Survey Water-Supply Paper 536 above mentioned, in these words: "The published figures for discharge in those months whose discharge-ratios vary widely from the yearly mean should be used with caution, and many of them should probably be adjusted after careful study of the discharge-record as published for the different stations. The discrepancies that cause the apparently inconsistent ratios are

discharges from records of tributaries--Concluded

River-discharge from tributary records and comparison yields gaged areas (G), ungaged areas (U), and total area (U + G)							
Drainage-area comparisons		Ratios (U + G)/G or lower river-discharge to gaged discharge		Departures of derived data from recorded discharges at lower river stations			Remarks (see footnotes)
Gaged	R [see notes]	Test-period	Checking period	Max. yearly	Mean absolute	Mean	
(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
pct				pct	pct	pct	
63.9	1.57	1.791	1.657	-20.1	± 8.2	- 7.5	f,h,k
74.3	1.35	1.396	1.439	+18.9	± 6.9	+ 3.1	f,h,k
.....	.....	1.396	1.438	+18.9	± 6.7	+ 3.0	f,h,k
28.1	3.55	1.671	1.657	+25.1	± 8.7	- 0.8	f,h,k
.....	.....	1.671	1.681	+25.1	±10.2	+ 0.6	f,h,k
28.1	3.55	1.547	1.759	+35.1	±15.5	+13.7	f,h,k
63.9	1.57	1.689	1.657	+15.1	± 9.3	- 1.9	f,h,k
18.3	5.46	5.594	5.755	+22.5	± 5.3	+ 2.9	b,m
.....	.....	5.594	5.615	.....	.....	+ 0.4	b,m
14.6	6.83	6.314	6.685	+23.8	± 9.1	+ 5.8	b,c,l
.....	.....	6.314	6.460	.....	.....	+ 2.5	b,c,l
11.0	9.10	8.260	8.100	-19.6	± 8.5	- 1.9	b,c,l
11.5	8.67	8.617	8.380	-14.6	± 6.3	- 2.8	b,c,l
11.5	8.67	8.274	8.380	+14.1	± 6.2	+ 1.3	b,c,l
38.7	2.59	2.562	2.543	- 7.8	± 3.7	- 0.7	b,c,l
.....	.....	2.562	2.504	.....	.....	- 2.3	b,c,l
37.2	2.67	2.739	2.669	- 8.0	± 4.4	- 2.6	b,c,l
.....	.....	2.739	2.635	.....	.....	- 3.8	b,c,l
33.1	3.03	3.077	3.003	- 9.1	± 4.4	- 2.4	b,c,l
.....	.....	3.077	2.999	.....	.....	- 2.5	b,c,l
33.1	3.03	2.954	3.003	+13.4	± 3.8	+ 1.7	b,c,l
.....	.....	2.954	2.999	.....	.....	+ 1.5	b,c,l
23.1	4.34	3.789	3.655	-22.7	± 8.6	- 3.5	b,c,l
28.8	.....	.....	.....	±30.7	±11.2	± 5.6	b,c,l,m

discharges with the total areas or discharges at downstream stations, provide valuable clues on which to extend the data, approximately, in terms of the longest records available. Examples include gaged areas representing from 1 to 90 per cent of the total drainage-area above Vicksburg, Mississippi, 1,144,500 square miles, at two to six stations.

Angola discharge-data, referred to under i in column (18), include the Mississippi - Atchafalaya River records at Red River Landing (Angola) and Simmesport (or Krotz Springs), Louisiana, respectively.

Tables 2 and 13, House Document 259, 74th Congress, 1st session, 1935, "Comprehensive report on reservoirs in Mississippi River Basin," by the Corps of Engineers, U. S. Army, yielded some basic data.

probably due mostly to inaccurate gage-readings and to variations in the runoff of Gauley River. In order not to have the published figures appear more accurate than the base-data warrant, no attempt was made to adjust these apparent inconsistencies. The rating-curves for the stations at Kanawha Falls and Lock No. 2 are based on measurements beginning in 1908."

The tests recorded in Tables 2, 3, and 4, numbered up to 44, actually comprise some 80 sets of comparisons of results from the "weighting-factors" and "sampling-method" (through index-areas) approaches to the extension of river-discharge data, also an incidental comparison with drainage-area ratios. These latter are shown in Column (12) of Table 4, adjacent to their reciprocals, expressed as gaged-area percentages of the total drainage-basin. In all of the Items 19 to 27, likewise in Items 29 to 31, and 34 to 44, as well as other scattered examples such as Items 18 and 18 A, the drainage-area ratios are nearly equal to the yield-ratios, [(U + G)/G], as explained in connection with the Tables, or total yield at the lower gaging-station divided by the gaged discharge of the tributary group. In contrast, the corresponding Items in Columns (12) and either (13) or (14) are about as 2:1 for Items 18 C, 18 D, 28, 32, and 33; similar data of Items 8, 9, and 17 are more nearly as 3:1. In other words, the gaged areas in the latter two groups yield from two to three times the average per unit of area, ordinarily per square mile in current practice, for the entire drainage-basin.

Mean absolute values recorded at the ends of Columns (8) to (10) and also (15) to (17), provide ready comparison of the results throughout the 80 tests. The maximum, mean absolute, and mean departures for identical checking periods prove to be 38.5, 15.0, and 9.0 for the average behavior of the weighting-factors, and 30.7, 11.2, and 5.6 per cent for the method comparing total yield with gaged tributary discharge. An apparent advantage seems to accrue to the latter method, on the average, as 5:4, 4:3, and 3:2, respectively, for values of maximum, mean absolute, and ordinary means in which the positive and negative cancel out in part. Nevertheless, in such Items as Nos. 5, 12 to 16, and 18 C, the situation is definitely reversed, and the approach through the weighting-factors is proved to have inherent advantages for solving some of the most extensive and complex problems. Actually, the two methods seem to supplement each other, often having departures nearly equal, but of opposite sign, thus providing a bracket about the most probable value of the unknown discharge, the item sought.

As illustrating the sensitivity of weighting-factors to irregularities in basic data and the reduced effect on departures, Items 18 and 18 A of Tables 2 and 4 show how not only the numerical values, but also the signs of weighting-factors are disturbed by an error of +8 per cent in one year's record of a relatively small tributary, the Kanawha River. Similarly, the same disturbance occurs between Items 19 and 20, where one year's record at the lower station for Item 20 was deficient by five per cent; yet maximum and mean departures are only slightly disturbed, in spite of the radical changes in weighting-factors.

The occasional maximum departure of 50 per cent or more should not be taken as seriously as a 20 per cent mean absolute, which reflects group-variations. Occasionally, only one or two years' data in a long period of record fail to satisfy the equation within fair tolerance limits. It seems to be characteristic of the maximum, mean absolute, and mean departures that they occur in series, either geometric or arithmetic, so that missing data may often be approximated by comparison with items covering similar groups of station-records and test-periods. Examining the data [H. R. LEACH, H. L. COOK, and R. E. HORTON, Storm-flow production, Trans. Amer. Geophys. Union, 1933, pp. 435-446] on Ralston Creek, Iowa River Basin, Iowa, it is found that Tables 1 and 2 provide representative data for a similar series, showing maximum, mean absolute, and mean departures of estimated discharge of Iowa River, derived from the 1.0 per cent sample-area of Ralston Creek, of 124, 33, and 13 per cent, where the quantities increase by a factor 3, approximately.

Recognizing the inherent differences between the problem of predicting daily and storm runoff from the Iowa River Basin of 3,230 square miles, as compared with estimating the yearly discharge for the lower Mississippi River from an area some 400 times as great, it is still evident that the problems have much in common. The variation applies to scale- and time-factors, more than to the objective, or to the methods of approach that may best serve in each case.

Conclusions

Painstaking and exhaustive tests, the most nearly representative and informative of which are summarized in the foregoing paragraphs and tabulations, have proved conclusively that

(1) The basic hydrologic data on tributaries may be related to the main river-discharge at a lower station as: (a) A ratio of either total or ungaged discharge to gaged discharge; (b) weighting-factors applied to the separate tributary discharges and to the residual ungaged discharge; or better (c) weighting-factors applied to gaged tributaries only, neglecting the ungaged area and contribution as separate entities, or else providing a constant as developed below under discussions.

(2) Within the limits of accuracy corresponding to the number of decimals employed, the weighting-factors obtained by the solution of simultaneous independent linear equations, in the same number as the unknown factors involved, will always satisfy each of the series of annual discharge-data for the years covered by the equations. Most of the Items in Columns (6) and (7) of Table 4 checked to within 0.01 per cent or less, with calculations carried out to six decimals.

(3) For years outside of the test-period, the derived weighting-factors applied to the yearly mean discharges of tributaries provide quantities which, in summation, should approximate the yearly mean discharge at the lower station. However, the agreement may be close, fair, or unsatisfactory, depending largely on the magnitude of the weighting-factors (necessarily increasing when minus signs are included) and the suitability of the test-period as showing the usual hydrologic relationships. The larger the factors and resulting magnification of influence traceable to individual tributary discharges, the more diverse the results seem to be. The simplest and most satisfactory series of values are those not very far removed from the yield-ratios of Columns (13) and (14), avoiding the minus sign. Changing from one test-period to another, or to other tributary-station records, may bring the acceptable series of weighting-factors.

(4) While the ratios of total discharge to gaged discharge usually bring results for years outside of concurrent record with maximum departures less than half the percentage of ungaged area, and the mean departures one-fourth or less of the ungaged percentage, the weighting-factors seem to disregard entirely the relative percentages of gaged and ungaged areas and the runoff-contributions therefrom. Thus a sample of ten per cent or even of one per cent, fortunately chosen, may perform more satisfactorily than a sample of 90 per cent in the formulas involving weighting-factors. For example, according to Item 18 D, the discharge from Greenbrier River, West Virginia, a minor tributary of the Kanawha, and the discharge of the Gasconade River at Rich Fountain, Missouri, representing only 0.4 per cent of the total drainage-area, give promise and partial proof of value in providing as reliable index-relationship as do the summations of considerably larger tributaries, widely separated throughout the basin, for forecasting the discharges at lower-river stations such as at Vicksburg, Mississippi, or Angola (Red River Landing) and Simmesport, Louisiana. Nevertheless, the unavoidable use of large weighting-factors in connection with such small sample-areas is subject to occasional wide disagreements due to magnification of small differences, as pointed out in the foregoing. Therefore, for general purposes, the larger tributaries are preferable for use as sample-areas on which to base estimates or observations for the lower-river stations, no matter what avenue of approach is used. When available records cover only minor tributaries, the weighting-factors approach, as well as the index-area method may be used to advantage. They seem to supplement each other, often erring on opposite sides of the correct value.

(5) The use of weighting-factors seems to provide indexes as to the dominant influences of tributaries governing the discharge at the lower-river station, and offers facilities for an independent approach to an estimated or derived discharge of the main river, nearly comparable in reliability to the ratio of either ungaged or total discharge to gaged discharge, discussed in the paper presented in 1941 before the Union [Trans. Amer. Geophys. Union, 1941, pp. 875-892].

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DISCUSSION

R. W. DAVENPORT (U. S. Geological Survey, Washington, D. C.)--The studies on which this paper is based, like most of the notable papers of which Dr. JARVIS has been author, have as one of their outstanding characteristics compilations of hydrologic data which for magnitude and scope are rarely equaled. These studies further establish his reputation as a tireless, persistent, and deep investigator in the field of hydrologic data.

One of the ideas investigated in these studies is that the yearly discharge at a downstream station may be placed equal to the sum of the products of the yearly discharge for upstream partial areas and certain weighting-factors to be computed from observation-equations. It is understood that in determining the weighting-factors a group of observation-equations was used equal in number to that of the unknowns to be solved. Another means of solution commonly used in such problems is to assemble all the pertinent observation-equations, although considerably greater than the number of unknowns, and by the method of least squares prepare normal equations and solve for the values of the weighting-factors which best fit all the observations. This procedure would be more laborious than that followed, but the results would be more significant scientifically.

To examine the significance of these weighting-factors a representative group has been selected from the tabulations in the paper for incorporation in the following equation (serial No. 11, Table 2) in which the several letters represent the discharges from partial areas and Q the discharge at the downstream station.

$$21.3425a + 2.7593b + 26.9060c - 3.1346d = Q$$

Representing the discharge of the ungaged area as U, the following equation may be arranged:

$$a + b + c + d + U = Q$$

Subtracting the latter equation from the former the following may be derived:

$$20.3425a + 1.7593b + 25.9060c - 4.1346d = U$$

Essentially the procedure seems to contemplate the applicability of a formula like that shown

in computing the discharge from the ungaged area for each year. The formula is necessarily adjusted to a composite of the conditions which prevailed in the four years for which the weighting-factors are computed. It does not give weight to factors or evidence which may be known in respect to the discharge of the ungaged area in individual years. Considering the vagaries of stream-flow distribution over large drainage-areas such as those of the Mississippi River and its major tributaries, it is evident that in many years the available meteorologic and hydrologic evidence might afford a much better expression of the ungaged discharge than could be obtained by a formula like that shown. The method does not furnish a sensitive means for estimating ungaged discharge and wide discrepancies in results particularly outside the period for which the formula is computed are therefore to be expected.

C. S. JARVIS--In response to the suggestions of Mr. DAVENPORT and others, recommending the alternate approach by the method of least squares, the writer has undertaken to satisfy himself and others by completing such a test. Following very closely the array of data employed for Item 19 in Tables 3 and 4, but extending the tributaries to include Red River at Garland (Arkansas) and the test-period to include 1933 to 1939--a total of seven years in order to provide for the like number of unknowns and normal equations--he found himself groping among coefficients ranging up to billions or even trillions. The labor and time required for the rigorous solution of seven simultaneous linear equations, with such cumbersome coefficients, beyond the capacity of ordinary calculating and adding machines, were approximately three times what was necessary for similar solutions by the simpler approach as set forth in the original paper. The results were interesting and illuminating, in that they brought fair agreement with the records of test-years, with a maximum departure of +4.6 per cent, and a mean absolute of ±1.8 per cent. However, when these least-square coefficients are used to compute values for the ten-year checking-period immediately preceding 1933, that is, for the years 1923 to 1932, the computed values show a maximum departure of +27.4 per cent and a mean absolute of ±8.3 per cent from Mississippi-Atchafalaya annual means as computed, estimated, or derived from the less satisfactory basic data for both the tributaries and the main rivers for 1923 to 1932 as contrasted with those for 1933 to 1939.

Inasmuch as the standards of the United States Geological Survey have governed the assembly of data for the seven-year period of test, 1933 to 1939, it seems appropriate to regard that period as the only period of accredited concurrent records on the lower river and the main tributaries. Prior data on the lower-river discharge may be regarded as fair approximations or derivations, but subject to considerable uncertainty.

In view of the foregoing, it appears that the writer has already used all the pertinent observational equations as suggested by Mr. DAVENPORT. The additional discharge-data for tributaries may be utilized to advantage by deriving (a) the long-period mean and (b) the short-period mean corresponding to the period of official record for the lower station on the main river. The relationships between these two means will indicate whether the concurrent records cover a period of deficient, mean, or excess discharge, and thus may guide in the proper evaluation of missing data.

An additional test was supplied by basic data for the years 1933 to 1938, utilizing the same stations as those included in Item 25 in Tables 3 and 4, that is, using data at Vicksburg and omitting records for Red River whose tributary junction is below Vicksburg. Solution of the normal equations yielded the results below (the actual values of weighting-factors were computed to seven significant figures in order that check-computations could be made).

Test-period	1933-39	1933-38
Lower-river stations	Red River Landing and Simmesport, La.	Vicksburg, Miss.
Weighting factors	cfs	cfs
Constant	-17,200	11,060
Ohio River, Metropolis, Illinois	1.2145	1.163,258
Mississippi River, Keokuk, Iowa	-0.3371	0.105,700
Missouri River, Hermann, Missouri	3.0544	2.081,342
White River, Clarendon, Arkansas	3.1107	3.111,428
Arkansas River, Little Rock, Arkansas	-2.6728	0.305,337
Red River, Garland, Arkansas	8.6671	.....

Similarities exist between the above constants and factors--but not the algebraic signs--and also between these values and those listed for Items 19 and 20 of Table 3, even though the time-periods covered by the tests are not the same. Under Item 19 of Table 4, it appears that a 50-year checking-period yielded maximum and mean absolute departures of only 19 and 5.1 per cent, respectively, each being only about two-thirds of the values developed for the ten-year test above

recorded. Similar departures are shown for Item 25 for a 21-year checking-period, with maximum and mean absolute departures of 23.6 and 7.6 per cent, respectively, as compared with 23.7 and 8.7 per cent resulting from the ten-year checking-period for normal-equation values at Vicksburg. Dr. N. C. GROVER'S advice is to adopt the simpler method of approach if the results are fairly comparable. Other tests may alter the trend. Other tests, including Item 66 below, afford further confirmation. The foregoing comparisons afforded by two sets of normal equations and also examples illustrating the author's approach are summarized below, along with related data.

Item	Approach by Least squares	Author's method of weighting-factors from simultaneous equations	
Lower gaging-stations at Red River Landing (Angola) and Simmesport, Louisiana	Item 45	Item 47	Item 49
Test-period	7 years (1933-1939)	7 years (1933-1939)	6 years (1933-1938)
Maximum departure	+ 4.6 pct	0.0 pct	0.0 pct
Mean absolute departure	± 1.8 pct	0.0 pct	0.0 pct
Checking-period	52 years (1889-1940)	52 years (1889-1940)	52 years (1889-1940)
Maximum departure	- 29.2 pct	+13.7 pct	- 20.4 pct
Mean absolute departure	± 7.9 pct	± 4.2 pct	± 5.8 pct
Lower gaging-station at Vicksburg	Item 46	Item 66	Item 32, Table 4
Test-period	6 years (1933-1938)	5 years (1934-1938)	2 years (1937-1938)
Maximum departure	- 2.1 pct	0.0 pct	0.0 pct
Mean absolute departure	± 0.9 pct	0.0 pct	0.0 pct
Checking-period	52 years (1889-1940)	52 years (1889-1940)	52 years (1889-1940)
Maximum departure	-29.4 pct	+18.2 pct	+20.4 pct
Mean absolute departure	± 6.7 pct	± 5.7 pct	± 7.9 pct

The above comparisons all show advantages with the simpler approach; based on either the same or shorter segments of basic data, these tests showed less departures over the 52-year period of record. Other tests based on either yearly or five-year means seemed to challenge the records for 1925, because the maximum departure occurred so frequently in that year. An error was found in published data for the Missouri River at Hermann, given as 20 per cent above instead of below the recent record-mean. Correction of that error benefited all six tests shown above, also that in Table 5.

Table 5 shows in detail the tests of weighting-factors derived from normal equations in accordance with the method of least squares. Therein it appears that the products of the respective weighting-factors and the associated mean yearly discharges, year by year, for the Missouri River at Hermann (Missouri) and for the White River at Clarendon (Arkansas), are frequently nearly equal. In many of the tests such products are of opposite signs, so that they incline to cancel out and to disappear except for small residuals, for several of the years. That characteristic is shown strikingly in the seven-year test by least squares as noted above, where the summations of products for the White and Arkansas rivers are within about five per cent of equality but with opposite signs, for both the seven-year test-period and the ten-year checking-period, or within one per cent for the eighteen-year period, 1923 to 1940. Similarly, opposing pairs were observed in the checking-periods for the author's method, underlying Table 4. Thus Item 7, wherein the Missouri River discharge at Fort Benton (Montana), multiplied by its weighting-factor, nearly cancels the like product for the Mississippi River at Keokuk: also Item 35, for Miami and Scioto rivers, and Item 40, for the Tygart and Tennessee rivers, in spite of their disparities.

Advantages have been claimed for the least-squares approach, and with good reason, in that observed data for any number of additional years of record may be incorporated in the basic equations. The author's method can accommodate such additional data with equal facility. As an example, we should recognize that official basic data, partly unpublished as yet, are available for two years, 1939 and 1940 not included in the six-year tests above noted. It seems desirable and logical to take the means of the respective discharges for the three calendar years, 1938 to 1940, and to substitute these mean values in place of those already used for the year 1938, thus spreading the basic data over the entire period of United States Geological Survey records now available. Arrays of weighting-factors for tests of various rivers reported above without such details, and for other notable ones, are given below as indications of the usual variations.

No.	Test-Period	Ohio, Metropolis, Illinois	Mississippi, Keokuk, Iowa	Missouri, Hermann, Missouri	White, Clarendon, Arkansas	Arkansas, Little Rock, Arkansas	Arkansas, Red Garland, Arkansas	Constant Vicksburg, Miss.	Constant Red R. Ldg and Simmesport, La.
47	1933-39	1.10781	0.66461	2.47372	3.22401	0.62462	1.39525	.....	-2,181
49	1933-38	1.21607	0.73957	1.49544	2.45520	1.34214	2.24935	.....	.....
66	1934-38	1.02131	0.25307	2.63770	3.10694	.....	.....	18,359	.....
67	1934-38	0.98428	0.62249	3.49267	4.17899	.....	.....	.....	-3,203
60	1924-38 (5-yr means)	2.34492	-2.69429	.....	4.35386	.....	.....	.....	.....

Table 5--Tests of weighting-factors derived from normal equations of least squares

(Checking by substitution of weighting-factors and constants associated with Mississippi River discharge at Vicksburg, to derive main river-discharge from records of tributaries)

Line No.[a]	Calendar years of concurrent records, estimates, or derivations, Mississippi River Basin								
	1923	1924	1925	1926	1927	1928	1929	1930	1931
1	341,021	343,475	218,797	321,292	478,448	339,974	397,078	204,826	139,591
2	4,154	5,570	3,911	5,919	7,336	7,547	7,166	4,143	3,361
3	158,453	168,693	104,066	170,837	287,850	200,100	214,399	114,682	95,887
4	155,571	87,120	68,451	74,674	230,246	164,128	159,990	90,200	63,566
5	21,975	10,681	5,493	12,510	29,914	14,473	17,190	8,885	7,716
6	11,060	11,060	11,060	11,060	11,060	11,060	11,060	11,060	11,060
7	692,234	626,599	411,778	596,292	1,044,854	737,282	806,883	433,796	321,181
8	+13.1	+ 6.7	+ 9.2	+11.7	+15.5	+ 5.9	+ 4.9	- 3.4	+ 1.2
9	612,000	587,000	377,000	534,000	905,000	696,000	769,000	449,000	317,300

Line No.[a]	Calendar years of concurrent records, estimates, or derivations, Mississippi River Basin								
	1932	1933	1934	1935	1936	1937	1938	1939	1940
1	319,896	356,655	180,654	338,741	269,643	396,555	292,210	323,502	224,672
2	4,661	4,351	2,894	5,850	4,866	5,145	7,879	5,340	3,907
3	135,287	107,397	67,789	164,821	82,879	115,390	125,588	103,568	65,417
4	72,216	102,242	53,268	138,147	35,968	99,566	118,234	108,900	59,117
5	10,504	10,778	6,134	20,482	4,430	9,545	13,642	6,351	4,244
6	11,060	11,060	11,060	11,060	11,060	11,060	11,060	11,060	11,060
7	553,624	592,483	321,799	679,101	408,846	637,261	568,613	558,721	368,417
8	- 0.8	- 2.1	- 0.4	+ 0.4	+ 0.3	+ 2.0	- 0.4	+ 3.2	+ 5.2
9	558,100	605,300	323,000	676,600	407,700	624,500	571,000	541,600	350,200

Note: The ten-year checking period is 1923-32. The six-year test-period is 1933-38, using data observed by the United States Geological Survey.

[a]Significance of lines as numbered, observed yearly mean discharge in cfs, as follows:
1 = Ohio River at Metropolis, Illinois, multiplied by weight-factor 1.163,258.
2 = Mississippi River at Keokuk, Iowa, multiplied by weighting-factor 0.105,700.
3 = Missouri River at Hermann, Missouri, multiplied by weighting-factor 2.081,342.
4 = White River, at Clarendon, Arkansas, multiplied by weighting-factor 3.111,428.
5 = Arkansas River at Little Rock, Arkansas, multiplied by weighting-factor 0.305,337.
6 = Constant in cfs for discharge at Vicksburg, Mississippi, as determined from normal equations.
7 = Summation of derived discharges of lines 1 to 6.
8 = Departure in per cent of line 7 from observed discharge given in line 9.

Such changes as have resulted through the use of the three-year mean from the values for 1938 are so nearly proportional as to forecast only slight changes in the weighting-factors. The new values will not satisfy the data from the individual years, 1938 to 1940, but only the three-year means in addition to the earlier five calendar years, 1933 to 1937, taken singly. A recently completed test involving the same stations as above listed, together with the Yazoo River discharge at Greenwood City (Mississippi), showed that the changes in weighting-factors resulting from the substitution of the means of 1939-40 in place of the data of 1939, were as follows, in the same order as listed above: Original values, 2.47364 1.26080 -9.42244 7.64465 6.43791 -19.8760 64,687 cfs, and revised values of 2.36937 1.28474 -8.85872 6.28513 6.66335 -16.8347 63,215 cfs. Use of revised values resulted in departures of -2.3 and +8.9 per cent, respectively, for 1939 and 1940. Value in Line 3, Table 5, for 1925 is one-third less than in Table 1.

In case there were a total of 30 years of basic data for the same tributaries and lower-river station, they would provide a series of six five-year means which could be used in place of the six-year array of records, thus incorporating all of the available basic information. In this manner any number of years of record may be subdivided into groups for use in basic equations.

If a homely illustration would be in order, the writer suggests that the seven years of concurrent record are comparable to bearing-piles in foundations. Cross-bracing may be advisable to insure unity of action and resistance against swaying, but no amount of such bracing or other superstructure can add to the vertical bearing power of the piles. Likewise, the cross-products may serve a useful purpose in tying the data together and locating the values corresponding to best fit, but they do not add one year of primary data to the array. Surely there are some compensations among the various methods. The writer prefers the use of the method used in connection with this paper, because of the simplicity of procedure, the saving of time, and the actual agreement within very close limits of tolerance for the years of test, depending on the number of decimals carried into results.

After having devoted much time to assembling the most pertinent of the available hydrologic data, both precipitation and runoff, as well as temperature-records for the Mississippi River Valley, publishing the findings in various technical and professional journals, and discussing the results freely with Mr. DAVENPORT and associates, the writer still feels that the early hydrologic data, particularly, should be subjected to such added tests and improved procedures as may be devised and found to have value. For most of these early data pertaining to the Mississippi River System, the application of weighting-factors as outlined in the current paper constitutes about the fifth approximation. The earlier estimates and derivations have been described in detail elsewhere, and include comparisons of excess or deficiency of rainfall and runoff, variations of temperature from normal, interpretations of hydrographs, rating-curves, and daily discharge-observations by various agencies--either official or unofficial--and such fragmentary data as are found in press-clippings, local diaries, and other records of the phenomena of weather, particularly concerning floods, drouths, and other noteworthy events. The harvest already realized through the use of weighting-factors has fully justified the investment, but there is much room for improvement of the procedure.

The persistent clamor for the application of least-squares procedure raises the question as to whether the proponents are depending on practical experience or upon theory. It is almost axiomatic that the arithmetic mean fulfills the essential criteria related to least squares, and is therefore a part of the procedure; yet it is advisable at times to use weighted means, such as would be involved in applying the THIESSEN method of computing depths of rainfall, thus departing from the least-squares approach.

The Department of Terrestrial Magnetism of the Carnegie Institution of Washington had to reduce the observed geomagnetic data collected on several hundreds of thousands of miles of cruises at sea. Because of the numerous data the first analysis, due to the need for prompt determinations of secular changes, was made by a simple approach completed within six months. Thereafter, when time permitted a least-squares adjustment, nearly three years were required by a first-class mathematician, well versed in least-square methods, to complete them; the results were nearly identical with those already derived by the simpler method.

With all due deference to the opinions of mathematicians, statisticians, and other technical specialists who have definite preferences for involved, cumbersome methods of analysis and procedure, the writer inclines more and more to the simpler, readily understandable methods that have proved their worth under practical tests. Only through distinctly superior performance can the more tedious, involved approaches be justified; and in such a case, the writer would gladly adopt any method that "pays its way" in the coinage of trustworthy and consistent results. We can afford to go great lengths to extend the boundaries of the known and to encroach upon the larger field of the unknown. Well-directed short-cuts may serve a useful purpose for reconnaissance, even though the arterial highway may be much longer to ease the gradients.

As has been pointed out repeatedly in the writer's recent contributions to technical paper discussions, particularly in the Proceedings of the American Society of Civil Engineers [October, 1941, pp. 1474-1482], it is harmful to develop an impressive veneer of involved technical procedures to give the appearance of greater exactitude than is inherent in the basic data. When the practical limitations as to accuracy of hydrologic data are recognized, whereby both depths of precipitation over drainage-basins and volumes of runoff are based on meager samples, subject in their turn to considerable instrumental errors as well as the vagaries of personal equations, it seems strange that anyone should expect consistent results from the method of least squares. It possesses no magic power with which to separate facts from fiction; it is well adapted to a rigorous analysis of unchallengeable basic data, but may possibly magnify some of the inherent errors and irregularities attaching to hydrologic data as they come to us now, as "run of the mill." The interlacing effect of cross-products, together with the magnification and comparison of differences as departures, may incorporate errors in basic observations of a higher order than the differentials we are seeking to isolate and interpret.

The harmonic relationships brought out in the course of solving the normal equations according to the method of least squares and the widespread use of this approach within its proper field have so established the Gaussian principles and methods as to insure their consideration in future problems. The writer acknowledges the valuable contributions to scientific research afforded by the method of least squares but urges that care be taken not to use those rigorous methods on basic data subject to the percentage of error inherent in standard stream-gaging and rainfall-observations over extensive basins, by means of a few scattered stations. Arithmetic means, or weighted means, or interpolations, extrapolations, extensive sampling, and other simple, practical means of comparison, may afford the required solutions with only a fraction of the investment in time and effort.

AN EXPERIMENT ON FLOW THROUGH A CAPILLARY TUBE

Robert E. Horton

A glass tube of 0.0736-inch or approximately two-mm bore was placed in a nearly horizontal position with one end slightly bent and immersed in a glass jar filled with water, as shown on Figure 1. For a given inclination of the tube the water flowed up the tube to such a distance from the outlet that the height of the capillary meniscus in the tube above the water-level in the jar was equal to the vertical height of capillary rise, in accordance with JURIN'S law. This distance L_c is given by the equation

$$L_c \sin a = c$$

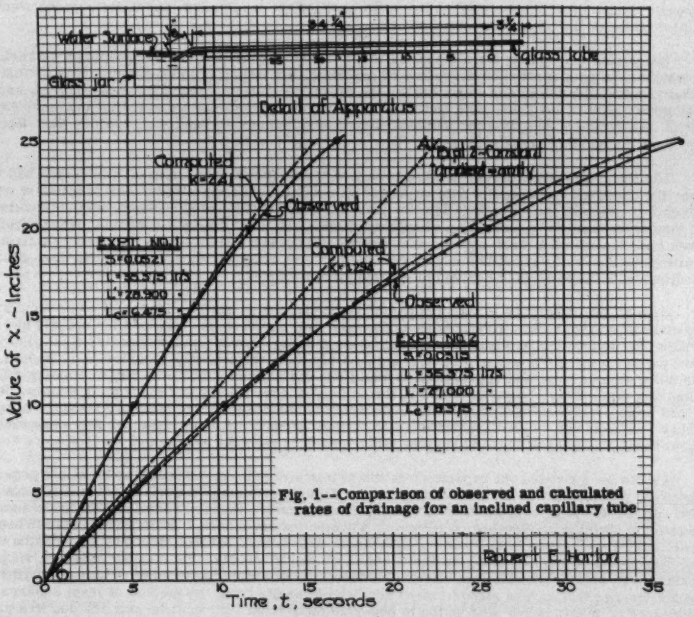

Fig. 1--Comparison of observed and calculated rates of drainage for an inclined capillary tube

where c = height of capillary rise in a vertical tube and a = angle of tube to the horizontal.

The tube was filled by suction, the upper end closed, and the tube then placed at a given angle and the inlet released. The water then flowed slowly down the tube, the rates of flow being determined by timing the passage of the meniscus along a scale adjacent to the tube.

In accordance with POISEUILLE'S law, as commonly applied in ground-water hydraulics, the rate of flow is proportional to the ratio of head to length of water-column in the tube. If the head is taken as the vertical distance from the capillary meniscus to the water-surface at the outlet, then, except for about one-inch immersion of the lower end of the tube, this ratio was constant for all positions of the meniscus in the tube in a given experiment, and the velocity of retreat of the meniscus should be constant.

The results of two experiments are shown on Figure 1, where t = time in seconds required

for the capillary meniscus to retreat a distance x, in inches, from the zero-mark on the scale alongside the tube. It was found that the rate of retreat of the capillary meniscus decreased with its distance from the outlet, the flow ceasing when the meniscus had retreated to a distance L_c from the outlet, where it was at a height c above the reservoir. These phenomena are readily accounted for if it is assumed that the effective head inducing flow in this case is not the total head from the reservoir to the meniscus but the vertical head from a height c above the reservoir to the meniscus. On this basis an equation for the relation between the time t and the distance x travelled by the meniscus can readily be obtained as follows.

If x is the distance of the meniscus from zero of the scale at time t, and K the velocity at gradient unity (a quantity corresponding to the transmission-capacity of a soil), L the length of tube from zero of scale to outlet, and $L' = (L - L_c)$, where L_c is the length of capillary advance in the tube, then from POISEUILLE'S law

$$v = (dx/dt) = K_t [(L' - x)/(L - x)] \quad (1)$$

$$K_t\, dt = [(L - x)/L' - x)]dx = [L/(L' - x)]dx - [x/(L' - x)]dx$$

On integration

$$K_t = x + L_c \log_e [L'/(L' - x)]' \quad (2)$$

Dotted lines on Figure 1 show the time-curves computed by equation (2) in two experiments. The slight excess of the observed over the computed times is at least partly due to the projection of the lower end of the tube into the reservoir. The experimental confirmation of equation (2) is very close. POISEUILLE'S law is confirmed if correctly applied. If, however, the capillary gradient was taken as unity, without deduction for capillary rise, POISEUILLE'S law gives a straight-line relation OA of time to distance x.

The experiments show that net or effective capillary head--not the gross capillary head--should be used in applying POISEUILLE'S law if correct results are to be obtained under the conditions of the experiment. The same thing is true in applying other flow-formulas, such, for example, as the MANNING formula for turbulent flow. The fact that the effective capillary head instead of the total capillary head should be used seems first to have been pointed out by HAGEN [see 1 of "References" at end of paper] and later by BOUSSINESQ [2] but without experimental confirmation.

PORCHET [3] performed many experiments on flow through soil-columns, using (1) soil-column fully submerged, (2) capillary surface within the soil-column, and obtained results similar to those obtained by the author in the latter case.

The results of one of PORCHET'S experiments are shown on Figure 2. Apparently PORCHET did not measure either the hydraulic head or the effective capillary head. He did measure the rate of outflow and the time, and found that the rate of outflow dropped off abruptly at the point α, Figure 2, at which the water-surface entered the soil-surface.

In subsequent discussion the following notation is used:

h_c = gross capillary head or difference between free-water level at the outlet and water-level in capillary menisci within the soil or capillary.
c = height of capillary rise.
h_n = net capillary head = $(h_c - c)$.
h_m = hydraulic or manometric head from free-water surface to free-water surface, as when measured in open wells.
b = minimum head required to initiate flow through extremely fine fissures, soil-interstices, or capillaries.
ℓ = length of substance through which flow takes place.

The term "capillary surface" is here used to describe the envelope of that portion of the capillary fringe in which the soil is completely or approximately saturated. In applying the equations homogeneous units must be used.

The author's experiments and those of PORCHET appear to be a particular application of a more general law. Numerous series of experiments have shown that flow through a given length ℓ of fine-textured substance, such as clays or rocks containing a large percentage of extremely fine

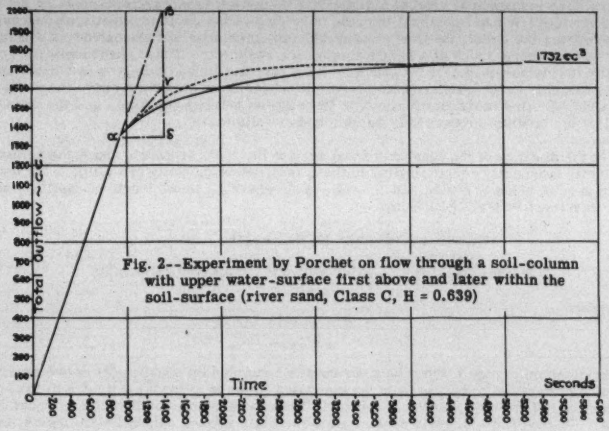

Fig. 2--Experiment by Porchet on flow through a soil-column with upper water-surface first above and later within the soil-surface (river sand, Class C, H = 0.639)

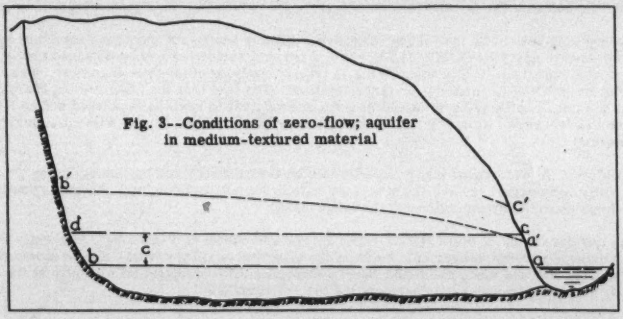

Fig. 3--Conditions of zero-flow; aquifer in medium-textured material

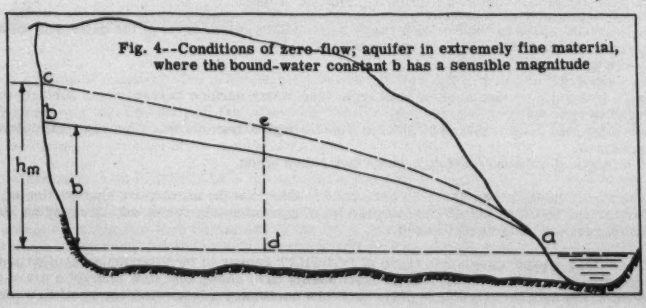

Fig. 4--Conditions of zero-flow; aquifer in extremely fine material, where the bound-water constant b has a sensible magnitude

pores or fissures, is zero unless the hydraulic head exceeds a minimum limit b [4]. This limit may be, and for dense substances often is, much greater than the length of flow through the substance. POISEUILLE'S law holds true for flow through such substances if the net effective hydraulic head (h_m - b) is used. Then

$$q = K_t [(h_m - b)/\ell] \quad (3)$$

where ℓ is the length of substance through which flow takes place.

Similarly, for flow in a capillary tube, under the conditions of the author's experiments, where b is negligible,

$$q = K_t [(h_c - c)/\ell] = K_t (h_m/\ell) \quad (4)$$

The identity of form of these two equations is suggestive. There is, however, a distinction between the two cases. The constants c and b are not identical. The constant b apparently corresponds to the effect of the "bound" water in the finer pores of the medium. For not too fine materials c may have values up to perhaps a few feet in natural soils, while b is sensibly zero. Flow then occurs for the slightest net capillary or hydraulic gradients, since in this case these two quantities are the same. In finer-textured materials the constant b is not zero.

Figure 3 shows conditions of zero-flow in an ordinary aquifer in not too fine-textured material where the constant b is zero or negligible. The line cd shows the capillary surface and the line ab the hydraulic grade-line, which in this case is horizontal. Water in the capillary stratum abcd below the capillary surface is in labile equilibrium with reference to horizontal flow. The section ac of the capillary fringe below the saturation-line is moist and glistens in sunlight but no outflow occurs. This is not a true seep-face. If the manometric surface is raised to a'b' a true seep-face aa' occurs below the intersection of the ground-water profile with the wall of the outlet, and water flows out of this seep-face. There is also a capillary face a'c' between the ground-water profile and the new capillary surface. Water in the layer abcd which did not flow under the first conditions assumed now partakes in flow toward the outlet.

Figure 4 shows conditions of zero-flow in a fine-textured aquifer where the constant b is of appreciable magnitude--in other words, where the capillaries are so small that all or most of the water is held as "bound" water by molecular forces until the hydraulic head exceeds the minimum value b for the given length of flow. In this case there would be no outflow with a ground-water profile ab but if the ground-water profile is raised to ac, flow would take place though not at a rate proportional to the manometric head h_m but at a rate proportional to (h_m - b). With the ground-water profile ac the water in the entire cross-section de would participate in the flow. Consequently for these conditions the flow would become zero or sensibly zero when the manometric head is less than b but when the manometric head is greater than b the rate of flow would increase much more rapidly than the manometric head increases. Thus it may happen that an aquifer which yields abundant water under ordinary hydraulic gradients may yield little or none if the hydraulic gradient falls to the minimum level (b/ℓ). Aquifers of this type are not likely to be of much practical importance if the texture of the matrix of the aquifer is uniform throughout. There are probably many instances of aquifers supplied by numerous rock-fissures where the size and frequency of the fissures decrease rapidly proceeding downward. Hudson River shale affords examples of rock of this type. Such aquifers may yield fairly abundant water when the ground-water profile is within the larger fissures close to the surface and the slope is great, but they may yield no water whatever when the profile has receded into the finer fissures and the slope has decreased to a value less than (b/ℓ), although in the latter case there may still be a definite positive hydraulic gradient or manometric head [5].

In such an aquifer the relation of head to flow-rate may follow POISEUILLE'S law closely when the head and yield are large but the flow may drop off much more rapidly if computed in terms of hydraulic head, with flatter slopes and lower water-levels.

Determinations in the laboratory of transmission-capacity are ordinarily made with a submerged soil-column, while in a natural surface-aquifer there is, as in the author's experiment, a capillary surface within the soil. The question arises whether transmission-capacities determined from a submerged soil-column are applicable to natural conditions. The author believes they are, for the simple reason that where there is a capillary surface within not too fine-textured soil, the hydraulic or manometric head $h_m = (h_c - c)$. Hence the manometric and effective capillary heads are in this case identical. The decrease in flow-rate in PORCHET'S experiments when the water-level fell within the soil-column was apparently caused by reduction of the effective

head, not by a change of transmission-capacity of the soil.

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DISCUSSION

C. E. JACOB (U. S. Geological Survey, Jamaica, New York)--Mr. HORTON'S paper presents the results of an interesting experiment in non-steady uniform flow in a slightly inclined capillary tube, the lower end of which was submerged in a vessel containing water. The water was drawn up in the tube by applying suction at the upper end and then was allowed to flow back into the vessel under its own weight. It was found that the rate of flow decreased continuously with time, the meniscus finally coming to rest at a height c above the free surface, equal to the capillary rise appropriate to the particular capillary radius. "These phenomena are readily accounted for," states Mr. HORTON, "if it is assumed that the effective head inducing flow in this case is not the total head from the reservoir to the meniscus but the vertical head from a height c above the reservoir to the meniscus." Then after deriving the equation of flow and comparing the results of his experiments with the theory he concludes that "The experiments show that net or effective capillary head--not the gross capillary head--should be used in applying POISEUILLE'S law if correct results are to be obtained under the conditions of the experiment."

It would seem that Mr. HORTON'S definition of the term "head" is such that he finds it necessary to introduce additional terms in describing the behavior of the retreating meniscus. In the writer's opinion the terms "gross capillary head", "net capillary head", "effective capillary head", and "capillary gradient" are superfluous. The quantity which Mr. HORTON designates by h_m and which he calls the "hydraulic or manometric head from free-water surface to free-water surface, as when measured in open wells," is generally called simply "head" in ground-water hydraulics and is designated by h. This is the variable that is to be substituted in the POISEUILLE equation $v = -(Kh/\ell)$. It is defined as the potential energy per unit-weight of fluid at a given point and is expressed by $h = [z + (p - p_a)/w]$, where z is the elevation of the point in question with reference to an arbitrary geodetic surface, p is the fluid pressure, p_a is the atmospheric pressure, and w is the specific weight of the fluid. It is obvious that at the free-water surface in open wells $p = p_a$ and $h = z$, the elevation of the water-surface. Differences in head are therefore measurable vertically "from free-water surface to free-water surface . . . in open wells" as Mr. HORTON suggests. However, if the well is of extremely small diameter the water-surface is no longer a "free" surface.

Consider a glass capillary tube of radius r submerged at its lower end in water. Owing to the relative magnitude of the three interfacial "free energies" inside the tube, the water-surface assumes the form of a hemispherical meniscus, convex downward. The pressure necessarily drops going downward across this curved surface, by an amount Δp, where $\Delta p = (2S/r)$, S being the "surface-tension" of water. As a consequence of the unbalanced pressures inside the tube (neglecting vertical variations in vapor-density), the water-surface rises until $[p_a + \Delta p - wz \text{ (inside)}]$ becomes equal to p_a (outside). Then $wz = \Delta p$, or $z = c = (\Delta p/w) = (2S/wr)$. If the datum is taken at the bottom of the vessel, the initial (and final) depth of water in the (large) vessel is h. At elevation $(h + c) = z$, just beneath the meniscus, the pressure is $(p_a - \Delta p) = (p_a - 2S/r)$. The final head at this point is $[(h + c) + (p_a - 2S/r - p_a)/w] = h$. In other words, the head is uniform throughout the body of water; the water is motionless.

It appears that Mr. HORTON has used "head" indiscriminately as being synonymous with "height". In the case of the capillary, the "height" of the meniscus above the free surface (the capillary rise) may be considered a negative pressure head at $z = c$, but the total head (or simply "head") is the same at that point as at any other point in the fluid while at rest. In order to be

precise in our nomenclature it would seem well to avoid saying "head" when we mean "difference in head" or "difference in height", and to use the modifiers "pressure", "geodetic", and "velocity" to describe the components of the head. Moreover, in any given problem the head should always be referred to the same datum.

In applying POISEUILLE'S equation to Mr. HORTON'S experiment, we may observe that if the meniscus is drawn up an inclined capillary by suction and allowed to fall, then at a given time when the meniscus is at elevation z the length of fluid-column resisting the flow is $z/\sin a = \ell$ (not unity), where a is the angle of inclination. We assume, as Mr. HORTON did, that the length of the submerged tube is small, and also that r is small enough so that gravity does not distort the meniscus. Then, since the problem is one of uniform flow, $(dz/dt) = v = (-Kh/\ell) = [-Kh(\sin a)/z]$. Expressing the head in terms of elevation and pressure, we get $h = (z - 2S/wr) = (z - c)$, whence $(dz/dt) = -K(1 - c/z)\sin a$. This may be integrated, after separating the variables, giving $K't = z_0 - z - c \log[(z - c)/(z_0 - c)]$, where $z = z_0$ for $t = 0$. By a simple change of variable this reduces to Mr. HORTON'S equation (2), and we thus arrive at the same result without having to introduce additional unnecessary terms.

The reference to the work of BOUSSINESQ given by Mr. HORTON is the same as that given by PORCHET. Apparently there was some misunderstanding on the part of PORCHET as to why BOUSSINESQ introduced the capillary rise into his equations and also as to the application of the equations as thus modified. BOUSSINESQ was concerned primarily with the flow of water in a shallow unconfined aquifer of great extent (relative to its thickness) and having small slopes (both top and bottom). He assumed, as had DUPUIT previously, that the flow-lines were virtually horizontal, that the planes of equal potential were vertical, and that therefore the vertical pressure-distribution was hydrostatic [see reference 2 of the paper, pp. 11-14]. Consequently his equation for nonsteady flow was in the form

$$\mu\,(dh/dt) = d[K(H + h)dh/dx]/dx = d[K(H + h)d\phi/dx]/dx \qquad (2)$$

with corresponding terms for the y-component of flow. Here μ is the specific yield, K is the transmission-constant, H is the depth below the datum of the base of the aquifer at (x,y), h is ordinate of the free surface at (x,y), and ϕ is the head (la charge) at (x,y).

In taking capillarity into account BOUSSINESQ explained (and this is quoted in part by PORCHET): "A une seconde approximation, il y aurait lieu de tenir compte de la réduction, que j'appellerai ξ, éprouvée par la pression p et par la charge ϕ, dans la nappe, à raison de la tension superficielle de l'eau . . . On aurait donc, non plus $\phi = h$, mais $\phi = (h - \xi)$; et il conviendrait de prendre ϕ, au lieu de h, comme inconnue; ce qui laisserait subsister entièrement, en ϕ, la forme de l'équation indéfinie (2), sauf la substitution, à la fonction donnée H, de la fonction analogue $(H + \xi)$. Car la hauteur (H + h) des volumes prismatiques élémentaires mouillés deviendrait $(H + \xi + \phi)$. . . . Rien ne sera donc changé à la forme des équations du problème ni, par suite, a la solution, sauf toujours la substitution, partout, de $(H + \xi)$ à H, jusque dans la hauteur de la section fluide intérieure, verticale et parallèle à X, fournissant le débit Q de la nappe" [Reference 2, p. 21].

In following BOUSSINESQ'S instructions one would rewrite his equation (2) as

$$\mu\,(d\phi/dt) = d[K(H + \phi + \xi)d\phi/dx]/dx + \ldots$$

Here $(H + \phi)$ is the apparent depth of flow, as might be determined from measurements of the head in observation-wells. In order to take into account the horizontal flow which takes place in the zone of complete "capillary" saturation overlying the water-table it is necessary to augment this depth of flow by the height of capillary rise, ξ, giving the expression enclosed by parentheses. But the capillary rise has no effect upon the horizontal, x-component of velocity, and hence $v_x = -K(d\phi/dx)$, as included in the foregoing equation. The capillary forces, in the aggregate, act vertically upward and therefore have zero, or nearly zero, component in the direction of flow, and this regardless of the texture of the soil. In the case of vertical free-flow, as studied experimentally by PORCHET and by Mr. HORTON, if the head is measured properly one should find that the flow follows DARCY'S law and that for the zone of complete saturation K remains constant--and independent of the boundary-conditions. Failure of PORCHET'S experiments to check with the theory (as seen, for example, by comparing the broken and full curved lines in Mr. HORTON'S Fig. 2) is to be attributed to his assumptions. He assumed the capillary rise to be equal to the supposedly constant reduction in head which began the instant the water-surface entered the sand, and computed it from the change in slope occurring at α on the flow-time diagram. This is perhaps not far from right initially, but capillary rise is a vague term. What is more serious, he

neglected the influence of the rate of fall of the liquid surface on the amount, distribution, and subsequent movement of moisture retained by the soil at a given point in the column. As pointed out by Mr. HORTON, PORCHET made no measurements of the head after the liquid surface entered the sand. If he had measured the head-distribution, let us say by means of piezometers spaced vertically along the column, and if he had been able to evaluate the equation of continuity for the entire column, taking into account the variations of moisture-distribution mentioned above, then doubtless he would have been able to revise his theory to fit his experimental results. It is interesting to note that although PORCHET had the right idea in introducing the capillary rise as what might be considered a "safety-factor" in designing systems of parallel horizontal drains, his equations were based on the "DUPUIT assumption" (that is, that the discharge per unit-length of drain is $q = -K \times y\,(dy/dx)$, which is not valid for the high slopes involved. It appears that this is the only problem, of the many he treated, in which the capillary rise was directly involved.

Following a statement to the effect that "numerous series of experiments have shown that flow through a given length ℓ of fine-textured substance . . . is zero unless the hydraulic head exceeds a minimum limit b," Mr. HORTON refers to the work of BALDWIN-WISEMAN. Then, later in the paper, he states in effect: ". . . aquifers supplied by numerous rock-fissures where the size and frequency of the fissures decrease rapidly proceeding downward . . . . may yield no water whatever when the profile has receded into the finer fissures and the slope has decreased to a value less than (b/ℓ), although in the latter case there may still be a definite positive hydraulic gradient or manometric head." This is followed by reference to MILLER-BROWNLIE'S paper. As far as the writer has been able to ascertain, in neither of these papers is there any support of this contention. Perhaps Mr. HORTON has in mind other "series of experiments."

BALDWIN-WISEMAN was concerned with sand-filters. He measured the rate of flow through actual filter-sands and through other, graded sands ranging in particle diameter from 0.0089 inch to 0.165 inch, under various gradients ranging from 0.5 to 40. It is obvious that many, if not most, of his data are for values of REYNOLDS' number above the critical.

In estimating the yield of irrigation wells, MILLER-BROWNLIE resorted to a rather curious device. He states: "It will be observed that I have calculated the cone as having straight sides and have added a few feet for the trumpet-mouth portion of the cone. The influence of the trumpet-mouth is only observed a few hundred feet from the tube, and the remainder of the curve being so nearly flat it may be considered the straight lines of an unrestricted hydraulic gradient. The error thus introduced is slight and the calculations very considerably simplified." Elsewhere he claims that observations in Punjab have shown that the "slopes necessary to cause water-motion have varied from one in 260 in moderately coarse sand to one in 175 in fairly fine sand." Thus it might appear that there had been some experiments. But, he states further: "Observations indicate that any lateral or forward motion of water, where the hydraulic gradients are slightly less than those mentioned, is so slow that for practical purposes it may be neglected, the actual velocity probably not exceeding a few inches per day" [underscoring is mine]. In view of the latter statement it is quite obvious that a minimum hydraulic gradient was merely assumed to simplify calculations.

Referring to Mr. HORTON'S Figure 4, which "shows conditions of zero-flow in a fine-textured aquifer where the constant b is of appreciable magnitude," one might naturally wonder, assuming b is constant (and presumably characteristic of the soil-texture), how the profile ab became established in the first place. According to Figure 4, b varies continuously from a maximum value at the left to a minimum value at the right. It would seem, therefore, that perhaps it is intended rather that there be a constant minimum gradient $(db/d\ell)$, and that equation (3) be written in the form $v = -K[(dh/d\ell) - (db/d\ell)]$. But if that were true, the profile ab should be a straight line.

O. E. MEINZER (U. S. Geological Survey, Washington, D. C.; communicated)--Mr. HORTON reports that in the experiment made by him the water moved in accordance with POISEUILLE'S or DARCY'S law. In his paper as published he also concludes that "transmission-capacities determined from a submerged soil-column are applicable to natural conditions." I am glad to note these conclusions because I believe they are firmly established by the thorough work of many competent investigators. DARCY'S law and its application to natural conditions are fundamentally involved in the quantitative work of the Ground Water Division, as is impressively shown in the recently published treatise on permeability and its field-application by L. K. WENZEL and V. C. FISHEL [W.-S. Paper 887].

After discussing his experiment, Mr. HORTON postulates a constant which he designates b, but he is careful to explain that this constant is not involved in his experiment and he presents no new evidence in support of its existence. He states that it has application to water in extremely

fine fissures, soil-interstices, or capillaries. Figure 4 shows hypothetical conditions where b is supposed to be of appreciable magnitude--"where the capillaries are so small that all or most of the water is held as 'bound' water by molecular forces until the hydraulic head exceeds the minimum value of b for the given length of flow." I shall not undertake to discuss the physics of exceedingly fine material, but it appears to me that if all the water is "bound" by molecular forces the material is impermeable and there is no flow through it, whereas if a part of the water is not "bound" that water is in a fluid state and obeys the laws of fluid mechanics, including DARCY'S law.

ROBERT E. HORTON (author's closure; communicated)--The discussion by Mr. JACOB exceeds the original paper in length. The first is in part repetitive and affords a complete confirmation both of the validity of the experiments and the law deduced therefrom by the author governing flow in a capillary tube with a capillary meniscus at one end, while the remainder of Mr. JACOB'S discussion is in part devoted to matters not entered into directly in the author's paper and which the author does not feel compelled either to accept or to answer.

There are some matters which require attention. Anyone who will take the trouble to translate the half-page quotation in French from BOUSSINESQ'S work will find therein nothing which in any way modifies the author's interpretation of BOUSSINESQ'S statement as cited by the author.

The distinction in types of "head" used by the author is neither unnecessary nor confusing. In case of the experiment described, the only head which could be directly measured is the total head. The net head, which governs the flow, can only be determined by deducting the capillary head from the total head [1].

The author is quite familiar with the meaning and physical interpretation of the terms he has used. An effort was made in preparing the paper to present it in language readily intelligible to persons with only a limited knowledge of the underlying physical problems and processes. The author does not wish to belittle in any way the desirability of rigorous presentation of a physical subject. Too often such presentation goes over the heads of those whom it might otherwise interest. The author believes that there is a "happy hunting ground" between the rigorous and usually tedious and pedantic, if not sophomoric, presentation of scientific results, on the one hand, and the still less desirable sketchy, so-called "popular", presentation.

Mr. JACOB'S derivation of the equation of the experimental curve gives the same results as the author's but is neither as simple nor as readily understood.

Mr. JACOB'S statement that capillary forces in the aggregate act vertically upward and therefore have zero or nearly zero effect, is obviously incorrect without limitation. In the author's experiment both gravitation and capillary pull act primarily in vertical directions. Under the conditions of the experiment the horizontal components of both of these forces are reduced in the same proportion when the tube is placed in an inclined position and the relation of the two forces remains unchanged, whether the capillary tube is vertical or inclined at an angle, as in the experiment. It is the difference of these two forces which operates to produce flow in the capillary tube.

Both Mr. JACOB and Dr. MEINZER refer to "DARCY'S" law. DARCY did not discover the law of capillary flow. It was discovered by POISEUILLE, and DARCY, finding that it applied to flow through filter-sands, properly credited it to POISEUILLE. It is primarily a law of physics--not of geology. The author has followed the nearly universal custom of physicists in describing it as "POISEUILLE'S law." Full credit for this law has been given to POISEUILLE, as it should be, in a recent paper by J. F. HERRICK [2].

The purpose of the author's experiment was to determine the effect of capillary tension where free menisci exist in capillaries in connection with certain problems not discussed in the paper. After the experiment was performed the author realized that it served to interpret rationally the results of PORCHET'S experiments. The author is aware of the various lines of work relating to ground-water carried out by PORCHET in addition to these particular experiments but does not feel called upon to discuss these other questions relating to that work which have been raised by Mr. JACOB.

PORCHET platted the rate of flow against time. There is an abrupt break in the experimental curve at the point where the water entered the soil-surface. MEINZER, JACOB, and the author are apparently agreed that this break does not represent a change in the actual transmission-capacity or permeability of the soil. It must, therefore, have been due to a change in the effective hydraulic gradient, and the occurrence of this break is simply and completely explained by the author's experiment.

The real bête noir underlying the discussions of JACOB and MEINZER appears to be the question whether there is a lower limit of direct applicability of POISEUILLE'S law to flow through fine-textured soils resulting from water in the finer pores of the soil being held as bound water at ordinary or small pressures.

Probably the author presumed too much in assuming that this subject would be familiar to those who would read or discuss this paper but regrets that it is wholly impracticable to give more than meager excerpts from the extensive literature on the subject, which is scattered through the literature of physics, hydrodynamics, and physical chemistry relating to the adsorption of liquids on solid boundaries--the non-existence of slip at the boundary in laminar flow, molecular orientation and association, the physics of unavailable soil-moisture, and the rheology of plastic and non-Newtonian flow. All this literature has a direct bearing on the question of what happens in case of extremely fine capillaries in the soil in which the water is bound at low heads or pressures but may become free and flow at higher heads or pressures.

Water apparently is a nearly perfect Newtonian fluid under ordinary conditions but becomes a non-Newtonian fluid close to a boundary-wall. This change is apparently due to a change of structure involving orientation of molecules and increased molecular association. These conditions have suggested that unfree water is of the nature of some form of ice [3].

The constant b, equation (3) in the author's paper, is the well-known yield-value for plastic flow.

The constant c is the height of capillary rise, and there is a corresponding constant where bound water plays a role in capillary flow, under conditions such as those in the author's experiment. As pointed out in the author's paper, b and c are not necessarily of the same physical nature. While in the case considered in the author's experiment, c actually is a constant, in a natural aquifer with pores of varying sizes from coarse to extremely fine, c is quite certainly not a constant. It has one value or may be negligible for the larger pores and has increasingly higher values as the fineness of the pores increases. Under these conditions the flow instead of being of identically the same nature as plastic flow, with a definite yield-value, as indicated by comparison of equations (3) and (4), would be more nearly of the nature of the flow of a non-Newtonian fluid [4]. Obviously it is difficult to experiment directly with flow of water at distances from the boundary-wall as minute as those involved where bound water is concerned. The existence of finite yield-values in fluids has, however, been determined experimentally in salt solutions by BLAIR and SCOFIELD [5, 6]. The relations of fluid-flow, pseudo-plastic flow or flow of a non-Newtonian liquid, and true plastic flow, seem first to have been pointed out by BINGHAM who has given [7, pp. 217 and 323] an equation similar in form to the author's equation (3). Later revisions of BINGHAM'S equations retain the same form.

Conditions of flow in a soil with very fine capillaries, under extremely slight pressures, are, however, further complicated by the usual presence of colloidal material with an extremely high water capacity--in fact, it is fair to say that no adequate, complete theory governing all the phenomena of flow close to a boundary-wall under such conditions has yet been formulated.

In a paper published in these Transactions [9], CHARLES H. LEE states:

> "Laboratory tests show that dense clays are absolutely impermeable under the hydraulic pressures ordinarily occurring in nature. This condition results from the compact arrangement of particles, interstitial spaces being so small that the forces of molecular attraction extend across them. Under such a condition, the forces of gravity and capillarity cease to operate and interstitial water becomes solidified."

LEE points out that such a soil may under suitable conditions be "slightly permeable because of numerous interstitial spaces which exceed the range of molecular attraction." This seems to be precisely the case referred to by MILLER-BROWNLIE [18].

B. A. KEEN [8] devotes an entire chapter to plastic flow and points out the identity of form of the equation therefor with the POISEUILLE law for flow through a capillary with a free meniscus at one end.

NORTHROP [10], discussing POISEUILLE'S law, states:

> "The simplest test of this law is the fact that the rate of flow is directly proportional to the pressure. With truly viscous liquids this is true over a wide range, provided the capillary is small. With low pressures it is frequently found, especially in the case of colloidal solutions,

such as gelatin [cf. BOGUE, 11], that the rate of flow decreases more rapidly than the pressure. This is an indication that the substance is plastic rather than viscous, that is, it requires definite force to cause a deformation of the mass. This is very apt to be the case in colloidal solutions due, presumably, to the existence of a definite structure [cf. McBAIN, 12]."

What happens in case of flow through a matrix of an aquifer containing pore-sizes ranging from large to extremely minute, under sufficiently low gradients, is that at larger gradients POISEUILLE'S law in its simpler form, as commonly used, gives highly exact results, for the reason that the percentage of pores in which bound water then exists is extremely minute. As the pressure-gradient becomes less and less, a larger proportion of the pores contain bound water, with resulting departures from the simple form of POISEUILLE'S law.

Finally, if the soil-texture is sufficiently fine, a minimum gradient is reached for which all of the pores contain bound water, and flow ceases. This may not be of much practical importance in case of most natural aquifers. It is, however, of considerable scientific interest and the underlying principles are of great practical importance in connection with certain other hydrologic phenomena which need not be discussed here.

STEARNS' excellent experiments on Fort Caswell (North Carolina) sand [W.-S. Paper 596-C, U. S. Geol. Sur.] afford accurate confirmation of POISEUILLE'S law as applied to this soil for larger heads but the same experiments for extremely small heads (two mm or less) on the length of sample considered show consistently larger departures from POISEUILLE'S law as the head decreases. For a head of 0.5 mm the actual flow-rate as shown by five consistent experimental values is little more than 50 per cent of that given by POISEUILLE'S law. As the head increases, the observed flow approaches that given by POISEUILLE'S law and the experiments for extremely low heads are well represented by a curve of precisely the type required for pseudo-plastic flow. These departures from POISEUILLE'S law do not appear to be capable of quantitative explanation as the result either of evaporation or variation of temperature.

Mr. JACOB has raised the question of MILLER-BROWNLIE'S observation regarding cessation of flow into wells in India in certain soils, under small gradients, and has called attention to experiments of MEINZER [16] and FISHEL [17] purporting to prove that this condition could not occur. Discussion of this question would be unprofitable here for the reason that, strangely enough, neither MILLER-BROWNLIE nor MEINZER and FISHEL give any specific information as to the fineness of the soil they are considering. From the preceding discussion it will be seen that whether flow will cease altogether or cease to follow the POISEUILLE law as ordinarily applied, depends entirely on the fineness of the finer pores in the matrix of the soil or aquifer.

To save space the author purposely cited only the latest of several papers of BALDWIN-WISEMAN of interest in this connection. The paper cited [3] contains [pp. 38-39] references to the earlier papers [14, 15]. It also states [p. 38]:

"The flow-conditions vary directly as the ratio h to L but at a slightly different rate, the variation being more marked at low pressures than at high pressures."

The experiments of BALDWIN-WISEMAN to which the author intended to call attention were those on flow through consolidated materials such as sandstones and oölites, not, as assumed by Mr. JACOB, the experiments on flow through filter-sands. The experiments on flow through rocks and consolidated materials are given in references [14] and [15], and platted directly as taken, they certainly do not confirm POISEUILLE'S law. It is interesting to note, however, that BALDWIN-WISEMAN found and definitely measured compression of the softer rock-samples (usually six inches thick) by water-pressure as low as five pounds per square inch. This pressure reduced the porosity, especially near the surface of the sample, and this must be taken into account in interpreting these experiments.

Finally, POISEUILLE'S law appears to be fully confirmed for practical purposes within a wide range of pressures and fineness of soil-pores. It is, however, subject to limitations in both directions, the upper limit occurring when the gradient and velocity become sufficiently great so that the flow in the larger pores is turbulent. The lower limit occurs when the gradient is so slight that water in the finer pores is no longer mobile but is held by molecular or capillary forces. The change of law of flow is not abrupt in either case in a soil or matrix containing pores of various sizes.

Engineers, physicists, and soil-physicists alike are generally familiar with the fact that water held in minute capillaries cannot be removed by gravity alone under ordinary natural conditions. The mere fact that these fine capillaries happen to be within an aquifer does not modify this.

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WATER-STORAGE BY CALIFORNIA HILL SOILS IN THE SEASON OF EXCESSIVE RAINFALL, 1940-41

Maurice Donnelly

Introduction

The hydrology of the excessive-rainfall season of 1940-41 in southern California is unusual. The season was marked by high-total rainfall and long-continued storms of moderate intensity. In view of the amount and distribution of the rains, especially in the peak-period in February and March, wide-spread, although not necessarily intense, floods were expected. That they did not materialize, except locally, is evidence of the large quantity of precipitation absorbed by soil. By some, this large volume of rain-water absorption is deemed to have resulted chiefly from the fact that, under the conditions of moderate-rainfall intensities, the soil, irrespective of the nature of the surface and of the type of vegetal cover, was able to take water in fast enough to reduce or prevent flood-producing runoff. Data presented here support an alternate hypothesis, namely, that reduction and retardation of storm-runoff was accomplished through the influence of plant-cover.

The data presented in this paper are from hill-culture studies made primarily to determine economic erosion-control measures for improvement of land-use in the lima-bean erosion-problem area of California, an area also known as the southern California fog-belt. The source of the data is the hill-culture field-station situated a short distance south of Capistrano on steeply rolling hills near the ocean.

Data

Meteorology--Insert A in Figure 1 shows monthly distribution of rainfall, 1940-41, at Capistrano in comparison with the long-time average monthly distribution at Los Angeles. At most stations in southern California, total precipitation for the year 1940-41 exceeded the normal by 100 per cent, or more. For example, the average annual rainfall at Los Angeles is about 15-1/2 inches; for 1940-41, the total was 32-3/4 inches.

Rains of late October, 1940, which were considerably heavier than normal, were quite warm. Air-temperatures in November were unseasonally high, and air-temperatures higher than normal continued throughout the winter and early spring. The rains, too, were prevailingly warm. The high proportion of days on which rain fell during the peak-period is notable--of the 23 days from February 11 to March 5, 1941, only eight were rainless.

Two types of storms may be recognized from time-intensity records. As shown in Figure 2, data from the first type plot as a comparatively smooth curve. At Capistrano, rainfall in this

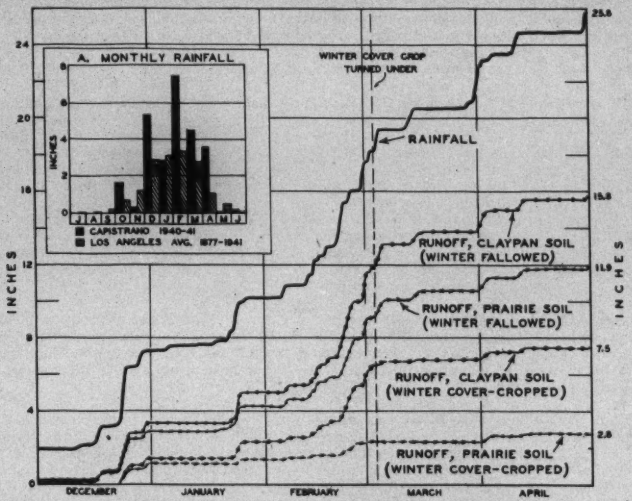


Fig. 1--Rainfall and runoff, 1940-41, Capistrano, California

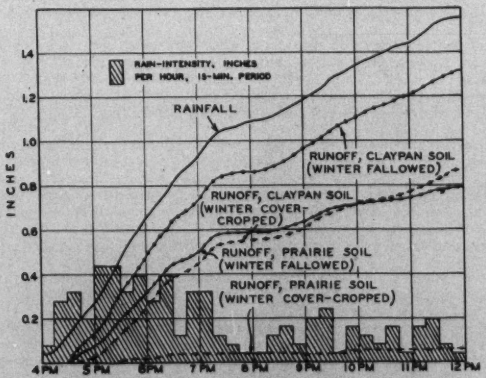


Fig. 2--Rainfall and runoff, February 28, 1941, Capistrano, California

type of storm seldom exceeded 1/2 inch per hour for a 15-minute period. In the second type (not illustrated), rain fell in bursts, followed by very light rains or rainless lulls. Intensities in these latter-type storms did not, at Capistrano, exceed 1-1/2 inches per hour for a 15-minute period.

Soils represented--Most of the measurements are from two soils that represent, in a general way, the hill lands used agriculturally in the coastal section of southern California. The first is Altamont, a primary soil developed on medium and fine-grained sediments. This soil, classified as a prairie soil [see 2 of "References" at end of paper] is generally deep, with moderate infiltration-rate and medium field-capacity. It typifies one of the better groups of agricultural hill soils of the coastal belt. The second is Tierra, a secondary claypan soil, probably to be classified as a planosol [1], developed over tight substrata. Ordinarily shallow, Tierra soil commonly has a low infiltration-rate and a medium field-capacity. It represents one of the poorer groups of agricultural hill soils of the coastal region. The Tierra and related soils puddle readily. Under cultivation their structure deteriorates quickly, and accelerated erosion is swift and damaging.

Typical profiles of Altamont and Tierra soils, as measured at the Capistrano station, are given below.

Altamont (uneroded profile)		Tierra (eroded profile)	
0 to 12 inches	Brown loam, friable	0 to 8 inches	Very dense grayish-brown clay
12 to 18 inches	Brown loam, slightly calcareous	8 to 18 inches	Mixed light- and dark-brown clay
18 to 30 inches	Light-brown loam, loose, moderately calcareous	18 inches and below	Tierra substratum
30 inches and below	Light-brown loam, loose, moderately calcareous		

Observations on Altamont soils include slopes ranging from 20 to 60 per cent; those on Tierra soils include slopes ranging from 15 to 18 per cent. Hydrologic factors were measured on uneroded, moderately eroded, and severely eroded Altamont soil. The Tierra soil studied is moderately to severely eroded. Uneroded profiles of Tierra soils were not studied because none exist at the Capistrano station.

Surface-conditions--Five surface-conditions were recognized: (1) In the first, the soil was bare and smooth at the start of the rainy season and remained so except for rills cut by surface-wash. Such a condition simulates winter fallow, a cultural practice widely followed on dry-farmed slopes in California. Bare slopes of this kind were common in the winter of 1940-41 throughout the coastal belt, on land that had been winter fallowed so long that few or no viable seeds were present in the soil, or on land where the early winter volunteeer cover had been turned under in November or early December, 1940. In the latter case, erosion was frequently so severe that a second germination of winter cover was depressed or prevented altogether.

(2) In the second condition, the soil was similarly bare and smooth in the fall of 1940, but was planted to a winter cover-crop that germinated in October and grew to a dense cover by the time it was turned under early in March, 1941. Such soil is said to be winter cover-cropped. A great deal of cultivated sloping land in southern California was in winter cover-crop, volunteer or seeded, at the time of peak-rainfall in February and March, 1941.

(3) In the third condition, a dense winter cover-crop, partly seeded and partly volunteer, had grown up on cultivated field-plots that had been contour-subsoiled to a depth of 16 to 18 inches in the fall of 1940. Although openings into the lower soil, made by subsoiling, had largely filled up by the end of December, contour-furrows produced by this tillage remained and were effective until the fields were disked in March, 1941. Subsoiling, on or near the contour, is a common practice in the coastal section, and much sloping land was protected by this method. Most subsoiled farm-land also developed a thick volunteer winter cover-crop.

(4) The fourth type of condition was that found on smooth-sloping uncultivated areas where a sod of perennial grass was present when rains began. This is referred to as "permanent cover."

(5) The fifth type of surface-condition was one in which sod covers the soil the year round, but in this case the sod is formed by low-growing winter annuals. This is referred to as "continuous cover." Pastures, which represent a goodly proportion of the total acreage in southern California, fall mainly in this final type.

Table 1--Permanent-cover plots

Plot No.	Soil	Slope, per cent	Exposure	Degree of erosion	Species
PC-1	Altamont loam	30	South	Uneroded	Chloris gayana (Rhodes grass)
PC-2	Altamont clay-loam	20	North	Moderate	Sanguisorba minor (small burnet)
PC-3	Altamont clay-loam	20	North	Moderate	Phalaris tuberosa var. stenoptera (Harding grass)
PC-4	Altamont loam	30	South	Uneroded	Paspalum dilatatum (Dallis grass)

Table 2--Field-scale plots

Plot No.	Soil	Slope, per cent	Exposure	Degree of erosion	Area sampled, acre	Surface-condition
FP-1	Altamont loam	25	South	Severe	1/7	Subsoiled and winter-cover crop (volunteer)
FP-2	Altamont loam	40	South	None	1/7	Continuous cover and young trees
FP-3	Altamont clay-loam	60	North	None	1/7	Continuous cover and young trees
FP-4	Altamont loam	35	South	Moderate	1/5	Subsoiled and winter-cover crop (sowed and volunteer)
FP-5	Altamont clay	25	North	Moderate	1/5	Subsoiled and winter-cover crop (sowed and volunteer)

On plots tested, winter cover-crop was composed, in varying proportion, of black-mustard (Brassica nigra), bur-clover (Medicago hispida), brome-grasses (mostly Bromus mollis and B. rubens), volunteer barley (Hordeum vulgare), annual blue-grass (Poa annua), and Italian rye-grass (Lolium multiflorum), with minor amounts of other annual grasses and weeds. The first two, mustard and bur-clover, comprised the bulk of the volunteer cover. Continuous cover-plots in annual ground-cover species consisted mostly of brome-grasses (Bromus spp.), bur-clover, and wild oats (Avena fatua), with much black-mustard in spots. These plots also bore young trees (Arizona ash, Fraxinus velutina and black locust, Robinia pseudoacacia) spaced 8-1/4 feet apart. Plots in perennial grasses consisted of pure stands of a single species, some in continuous matted stands, others spotty with bare spaces between plants. At the period of heaviest rainfall in late February and early March, 1941, grasses and bur-clover had reached heights ranging from one to three feet; the mustard had reached heights ranging from five to eight feet. Dense growth covered most of the vegetated plots; on many, roots grew plentifully at the ground-surface during the wet-test periods. The density of growth on winter cover-cropped plots was unusually heavy; samples taken in late February, 1941, indicate that the total green matter at that time was about five tons per acre on the heavier soils (Tierra) and as much as 20 tons per acre on the lighter soils (Altamont).

Kind of measurements made--The three groups of plots used in this study are designated permanent-cover plots, field-scale plots, and runoff plots. Rainfall was determined for all three groups by a net of three recording rain-gages located at the vertices of an equilateral triangle having a length of side equal to 500 feet. Other measurements varied with the respective groups.

The first group of plots consists of small areas, 4 by 16-1/2 feet, in permanent cover of perennial low-growing vegetation. They are replicated twice on each exposure. These plots, listed in Table 1, were sampled for moisture-content on significant dates. Results are reported for small burnet (Sanguisorba minor, a perennial herb, but not a grass), Rhodes grass (Chloris gayana), Harding grass (Phalaris tuberosa var. Stenoptera), and Dallis grass (Paspalum dilatatum).

On the second group of plots, designated field-scale plots because they are in the range of size of small farm fields, measurements of soil-moisture were made on significant dates, along with visual observations on runoff and erosion during the season. See Table 2 for a list of these field-scale plots.

On the third group of plots, called the runoff plots, measurements were made of runoff (both intensity and storm-totals), soil-moisture, and cover-crop weights. These plots are 13.2 by 13.2 feet, 0.004 acre in area. Table 3 lists these plots. Intensity and amount of runoff from these plots

Table 3--Water balance sheet for runoff plots, Capistrano, California, season of 1940-41 (to March 17, 1941)

Soil and plot No.	Surface-condition of plots	Seasonal rainfall	Runoff	Soil-water storage	Storage plus runoff	Consumptive use to March 17, 1941		Green weight of cover-crop February 27, 1941
						Evaporation from soil	Transpiration and evaporation	
		inches	inches	inches	inches	inches	inches	tons/acre
Altamont loam[a]								
RO-1	Bare	20.6	10.4	6.2	16.6	4.0	....	.....
RO-4	Bare	20.6	10.7	5.9	16.6	4.0	....	.....
RO-2	Cover-cropped	20.6	2.6	8.7	11.3	....	9.3	11.5
RO-3	Cover-cropped	20.6	2.0	10.3	12.3	....	8.3	10.0
Tierra clay[a]								
RO-6	Bare	20.6	13.1	3.4	16.5	4.1	....	.....
RO-7	Bare	20.6	14.5	1.9	16.4	4.2	....	.....
RO-5	Cover-cropped	20.6	7.0	4.2	11.2	....	9.4	5.8
RO-8	Cover-cropped	20.6	6.6	5.1	11.7	....	8.9	5.2

[a]Altamont-loam plots, south exposure, slope 36 per cent; Tierra-clay plots, west exposure, slope 18 per cent.

were measured by devices that follow closely the design and operation of the tipping-bucket rain-gage. Runoff-water, collected at the bottom of plots, is passed through a tipping-bucket mechanism that records on a roll-type chart actuated by a clock. The record gives intensity and amount of runoff. Discharge-water from the tipping bucket is collected in a calibrated tank, where it is measured at the end of a storm and is then passed into settling tanks where the soil-washoff is separated by elutriation and evaporation (fine soil-particles settle out and water passes out of settling tanks as clear overflow or by evaporation). Soil-washoff is weighed as total for season, or for part of season.

Soil-moisture sampling was made by the customary procedure, samples being obtained at a given horizon by coring with a soil-tube. Moisture-content, obtained by determining field-weight and weight after drying at a temperature of 105°C, is expressed as a percentage of dry weight of soil. Sampling extended in most cases to a depth of nine feet, exceptionally to a depth of 12 feet. In depths less than nine feet, the limiting factor was the impenetrability of the soil to the soil-tube.

In Figure 3, the position of the line showing field-capacity is approximate. Field-capacity is that useful concept in the physics of soil-moisture introduced by VEIHMEYER to designate the amount of moisture that a soil will hold at equilibrium against the pull of gravity. Two things need to be satisfied in determining field-capacity. First, sufficient water must be added to bring a given soil-column to a state at which the moisture-content equals or exceeds the amount at field-capacity. And second, sufficient time must elapse after the addition of water for the moisture-increment above field-capacity, if any, to be drained off by gravity pull. Field-capacity in the cases cited in this study, was determined by measuring soil-moisture under conditions that satisfy the two foregoing stipulations.

The march of soil-moisture throughout 1940-41 was determined on the runoff plots, on field-scale plots described as subsoiled and winter cover-cropped, and on representative permanent-cover plots.

Water-relations on runoff plots--Cumulative runoff from these plots is shown in Figure 1. A record of rainfall and runoff from a single storm on February 28, 1941, in the middle of the wet-weather period, is shown in Figure 2. Hydrologic data on the performance of these plots in the season of 1940-41 to March 17, 1941, are shown in Table 3. March 17, 1941, is the first soil-moisture sampling data after cultivation on March 3, 1941.

Runoff from these plots in the early part of the season (October and November, 1940) was slight from winter-fallowed (bare) soil and nil from winter cover-cropped soil. No runoff was shed from any of these plots from the light rains of May and June, 1941. Thus the cumulative runoff-curves shown in Figure 1 are complete for the entire season as regards the cover-cropped plots and complete for the entire season for the bare plots except that the small amounts of runoff shed from early-season storms are indicated by vertical intercepts on the time-line of December 1, 1940.

Soil-moisture sampling of the plots listed in Table 3 extended to a deeper horizon than the zone of maximum moisture-penetration. There was no evidence in this sampling of net gain or net loss of moisture by lateral flow.

On March 3, 1941, the runoff plots were cultivated. Winter cover on the cover-cropped plots was turned under as green manure, the bare runoff-plots were spaded on the contour. After this time, 7-1/2 inches of additional rain fell, an amount equal to about one-half the total normal rainfall. The runoff, from this 7-1/2 inches of rain, from these plots is given below.

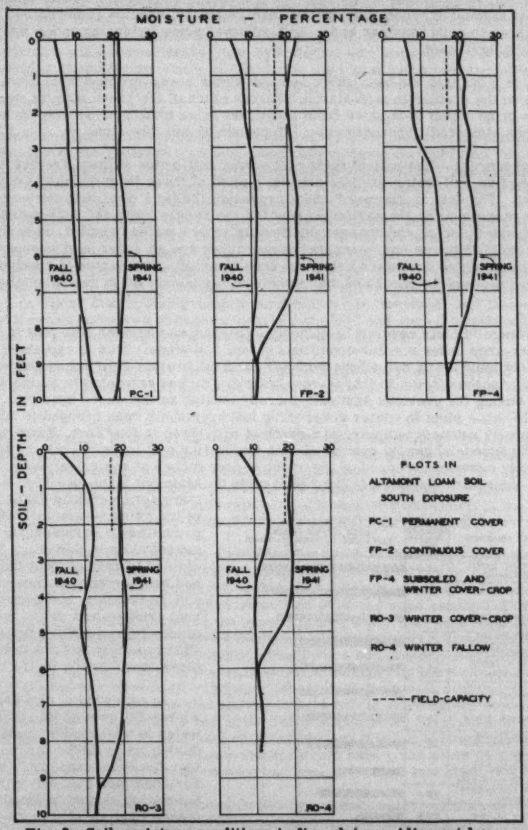


Fig. 3--Soil-moisture conditions in five plots on Altamont loam, south exposure, under different surface-conditions, Capistrano, California, 1940-41; plot-symbols correspond to those in Tables 1, 2, and 3; left-hand curves show soil-moisture percentages in fall of 1940 just before rainy season began and right-hand curves those in spring of 1941 when soil-water storage was at or near peak for season

Runoff-plots[a]	Soil	Surface-condition	Weight of green manure,[b] tons/acre	Runoff,[b] inches
1 and 4	Altamont loam	Bare, spaded	0.0	2.8
2 and 3	Altamont loam	Green manure spaded under	10.8	0.5
6 and 7	Tierra clay	Bare, spaded	0.0	4.0
5 and 8	Tierra clay	Green manure spaded under	5.5	1.0

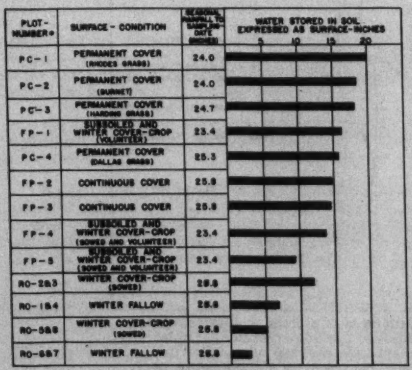
[a]Plot-numbers refer to those in Table 3. [b]Average of two plots.

Despite the low amount of runoff from green-manured plots, erosion removed soil in amounts of the order of three to eight tons per acre. Soil-removal prior to turning under the winter cover-crop had been insignificant.

Field-scale plots that had been subsoiled and winter cover-cropped were first cultivated by rough disking on the contour in mid-March; because much of the green manure was left at the surface, little or no runoff took place from additional rains totaling about five inches. Erosion on these fields was almost nil, approximating 100 pounds of soil per acre.

Soil-water storage--The salient facts concerning soil-water storage are set forth in Figure 4. Figure 3 shows five soil-water-storage graphs, typical of those from which the data in Figure 4 were computed. The data in Figures 3 and 4 represent the time when soil-moisture storage was at or near the maximum for the particular plot for the season 1940-41. Soil-moisture storage is, of course, a dynamic factor and changes continually as new water is added, as moisture is evaporated from the soil, as plants use water by transpiration, and as water held temporarily above the field-capacity percolates downward below the zone sampled. The period of maximum storage was determined by following the march of soil-moisture (not described in detail here) on representative plots.

Water-storage in plots covered by perennial grasses was greater than that in field-scale plots in winter cover-crop under similar conditions of soil and slope. This is explained partly by the superior infiltration-rate of soil whose structure and infiltration-rate are enhanced by deep-rooted, fibrous grass. Another factor is that these perennial grasses extracted to a high degree the water from the soil during the previous summer, thereby leaving an increased space for moisture-storage. Field-scale plots in winter cover-crop had previously been cropped to lima beans, a plant that normally extracts moisture to a depth of only three to four feet. Extra water-storage in soil covered by perennial grass, compared with that of like soil in field-scale plots cultivated to beans and winter cover-cropped, is of the order of four inches of equivalent water in the cases studied. Soil-moisture conditions in the runoff plots on Altamont loam (see Fig. 3, RO-3 and RO-4) were not so greatly different at the start of the rainy season in 1940 from those prevailing in permanent-cover (perennial grass) plots in this soil. This is explained by the fact that these runoff plots had been cropped to beans only one year and, previously, had been covered by annual grasses and weeds that had extracted much of the moisture from lower levels. This moisture had not been replaced at these lower levels by the rains of 1939-40.



* PLOT-NUMBERS CORRESPOND TO THOSE IN TABLES 1, 2, AND 3

Fig. 4--Water-storage diagram, 1940-41, Capistrano, California

In every case, except for one of the winter-fallowed plots (Tierra clay), soil-water in appreciable quantity was stored during wet weather to a percentage higher than the field-capacity in the upper soil-horizons (see Fig. 3). This water of saturation ranged in amount from a few inches to as much as nine inches of equivalent surface-water. In June, 1941, slow seepage of water to lower depths brought some of the deeper horizons to a moisture-condition above the field-capacity. As late as the fall of 1941, some of the soils saturated above the field-capacity had not reached equilibrium in the lower horizons.

During the stormy period, there was little evidence of net loss or gain in water at any particular horizon by lateral movement of water. Such lateral outflow as may have taken place appears to have been compensated by lateral inflow. The few soil-moisture records that did appear to indicate lateral flow were discarded in computing soil-water storage.

Discussion

From a consideration of the soil-water-plant relationships, the outstanding feature of the rainfall-season of 1940-41 in southern California was that conditions were unusually favorable for the development of winter cover. Any analysis of the year which overlooks or de-emphasizes this feature is incomplete. Despite the moderate intensities of precipitation that prevailed, water-retention by soils not under the dominating influence of plant-cover could not have accounted for the lack of floods on a wide-spread scale. The hydrologist will be particularly interested in the unusual development of protective winter cover, in the high total and moderate intensity of rainfall, and in the relative lack of floods and flood-damage, except where these were induced by bare or poorly vegetated land.

Though conditions for the development of winter cover-crop were highly favorable, much dry-farmed land in a few of the southern counties, especially in Santa Barbara and Ventura counties, went through the winter season of 1940-41 with little or no plant-cover. The explanation for this lies in the system of winter-fallow cultivation practiced on these lands. Elsewhere, such land, although fallowed at the beginning of the season, had enough viable seed in it that a cover germinated and, where left undisturbed, made heavy growth. In Santa Barbara and Ventura counties, however, many fields have been winter fallowed so long that viable seeds are scanty or absent in the upper soil where germination can take place. Then, too, in these counties the practice of winter fallowing is a long-established one, and winter cover on dry-farmed fields is consequently disked under as soon as possible by the majority of farmers. Thus the early cover that did appear on some of the fields, long in winter fallow, was promptly turned under in November and December. The relation between these occurrences of bare or nearly bare land and such flood-damage as did take place in 1940-41 in southern California was immediate and obvious.

Few data have been reported on the effect of steep slopes on runoff. Those reported in this paper support the general view, that increase in runoff does not bear a uniform relationship to increase in slope.

The question naturally arises as to what effect the retention of large quantities of water in the soil had on landslides and related mass-movements of soil and mantle rock during and following the wet weather of 1940-41. In southern California, landslides and related movements were infrequent in 1941, although by no means absent. In the permanent-pasture areas of the Benicia District in Solano County, in middle California, soil-slippage was excessive in the 1940-41 season (written communication to the writer from Professor MARTIN R. HUBERTY).

There appear to be several reasons why landsliding and related earth-movements in southern California were limited in 1941: (1) In 1938, landsliding and soil-slippage was wide-spread following extremely heavy precipitation in March of that year. Hence, many sites that had become unstable over a period of years, underwent movement in 1938 and were readjusted to a condition of comparative stability. (2) The nature of the penetration of water into the soil in 1940-41 was such that there was little development of sloping boundary-planes between a highly wetted soil above and a comparatively dry soil below, a condition that favors soil-slippage. (3) On sites covered by winter cover-crops, moisture was used in considerable amounts by the vigorously growing plants, a situation that tended to prevent soil-slippage. (4) Much of the winter cover-crop consisted of plants having long spikelike taproots that served to hold soil in place against downhill mass-movement. Nevertheless, toward the end of the rainy season in April, it seemed to the present writer that mass-movement was imminent on many slopes; it is his opinion, which must be accepted merely as an opinion, that earth-movements would have taken place on a wide scale in southern California in 1941 if the rainy season had been prolonged into May.

Another unfavorable product of excessive storage of soil-water, such as took place in southern California in the rainy season of 1940-41, comes from the damage this causes to certain tree-crops, especially to avocados planted in heavy, poorly drained soils. This type of damage, known in the case of the avocado as "decline", exacts a heavy toll.

Summary

In the excessive-rainfall season of 1940-41 in southern California, early warm rains

germinated a winter plant-cover on all soils, except where some special scheme of cultivation prevented it. The growth of this cover was benefited by rains of December and January and by the prevailing warm air and rain-temperatures. By the time of peak-precipitation in February and March, dense plant-growth covered most of the land. This growth exerted a marked influence in reducing and retarding runoff. Water in large volume was stored in most soils. In the cases examined in this study, water stored (at or near the peak) in well-vegetated prairie-soil was equivalent to 10 to 20 inches of surface-water, or 40 to 80 per cent of the total precipitation. Water stored by vegetated claypan-soil (planosol) was equivalent to four to five inches of surface-water; but where such soil was well vegetated, total moisture-retention was equivalent to 18 inches of surface-water, or 75 per cent of the total precipitation.

Acknowledgment--The writer is particularly indebted to Professor MARTIN R. HUBERTY, of the University of California at Los Angeles, for advice and criticism in this study.

References

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[2] Soil Survey Division, Bureau of Chemistry and Soils, Soils of the United States, U. S. Dept. Agric. Yearbook, pp. 1019-1161 (pp. 1052-1053), 1938.

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DISCUSSION

N. E. EDLEFSEN (University of California, Davis, California)--The storage-capacity as usually interpreted by soils investigators is fixed by the soil, that is, by the texture of the soil as well as the depth. As used in this paper, however, the storage-capacity is assumed to be not only dependent upon the texture and depth of soil, but also upon the amount of water already in the soil. The author uses the term to mean the amount of water that can be added to an already partially filled soil.

The reader is left in doubt as to whether or not the soil-moisture data furnished were obtained from the plots from which runoff was measured. Data showing the permanent wilting-percentage for each depth of soil, as well as field-capacity, as measured by the moisture-equivalent, would be desirable. It would seem that such data are pertinent to a rational interpretation of those measurements which were made. The reader is not certain that rainfall minus the storage, as measured by soil-sampling, minus the runoff equals the evaporation plus the transpiration, since some may have percolated through the soil.

Water usually is absorbed by a dry soil faster than it is by a comparatively wet soil. It is not surprising, therefore, that the runoff from the plots which had been dried out by growing crops, was less, early in the season, than that off those plots which were comparatively wet and upon which no plants were growing. As mentioned above, however, we are not certain that this has been shown to be true in this paper since pertinent data are not presented.

The limited amount of data presented do seem to indicate that the runoff is less from areas upon which a dense cover-crop is growing and which has dried out the soil, than it is from plots which were partially wet at the beginning of the rainy season and upon which no crops were growing. This effect, however, may be appreciable only during the time required for the rains to fill up the soil, that is, to wet it to field-capacity or slightly above.

There is another effect which may help in this same direction. The growth on the covered plots may slow down the runoff and thereby give more time for penetration. The author of the paper does not separate these two effects.

California hill soils under range-conditions are usually dried out to at least the permanent wilting-percentage, before the end of the growing season. Thus the soils have been completely dried out, as far as plants can do so, before the beginning of the rainy season. High runoff from such soils seldom occurs until sufficient rain has fallen to saturate or at least to wet up the soil to the field-capacity. It is seldom that California hill soils, which for the most part are shallow, are not supplied with sufficient water so that the rate of infiltration is markedly reduced, long

before the rainy season is over. Thus if high rates of rain occur after this stage, high rates of runoff can be expected. On cultivated areas, however, it is clear that the amount of rain required to fill up a given soil will depend, to some extent, upon the character of the crop or character of the practice during the growing season, since some plants will dry out the soil to a greater depth than will others, depending upon their rooting habit. Except for the surface-layer where direct evaporation takes place, all plants will, however, dry out a given soil to approximately the same value, the permanent wilting-percentage.

The author's inadequate data from small plots give little support to his contention that the cover-crop started by early rains in the season of 1940-41 "..... exerted a marked influence in reducing and retarding runoff." He presents no data to afford a comparison of runoff during this season, from plots treated in a given way, with runoff from such plots during other years when the rates of rainfall were higher.

SOME OBSERVATIONS OF THE THERMAL QUALITY OF SNOW

Walter T. Wilson

In relating the melting characteristics of snow to the resultant runoff, an important factor is the amount of heat required to melt a given quantity of snow. This must be examined in evaluating computations, observations, or forecasts of rate of heat-supply.

It may be recalled that the amount of heat necessary to melt pure dry-ice is 80 cal per gr or 144 btu per lb. As snow melts, it becomes a mixture of ice-crystals and water. The thermal quality may be defined as the percentage, by weight, of ice in the mixture. Partially melted snow does not consist of molecules in a state between liquid and solid, but is a mixture of wholly frozen ice-particles and wholly liquid water. Thus the quality, in per cent, is a factor, which multiplied by 80 gives the number of calories required to melt a gram of snow. For example, snow having 90 per cent quality is 90 per cent ice and 10 per cent water (neglecting the weight of air in the snow). Furthermore, the amount of heat required to melt this snow is 90 per cent of 80, or 72 cal per gr. Snow with subfreezing temperature has a quality greater than 100 per cent because of the additional heat required to raise the snow-temperature to freezing.

The holding of liquid water by a matrix of ice-crystals is analogous to the retention of moisture in soil. An important difference, however, between snow and soil with respect to their moisture-content is the obvious impossibility of measuring the quality of snow by baking or by a centrifuge. Heat-transfer to or from the snow changes the quality of a sample being examined. The thermal quality of snow may be measured by observing the amount of heat required to melt the snow. A satisfactory method is adding hot water to a sample of snow, using a vacuum bottle for a calorimeter.

Records of a few isolated tests of the amount of heat required to melt snow appear in hydrologic and thermodynamic literature, but only recently have efforts been made to accomplish this by practical field-methods. The technique is described in a series of technical bulletins issued early in 1941 by CARROLL F. MERRIAM, when he was Chairman of the Research-Committee of the Eastern Snow-Conference, and in a paper "A new technique for the determination of heat necessary to melt snow", by MERRILL BERNARD and the writer [Trans. Amer. Geophys. Union, 1941, p. 178]. The word "quality", chosen by analogy between wet steam and wet snow, has good precedent in mechanical engineering terminology, and was suggested in a conversation with H. C. S. THOM. Mr. MERRIAM suggested that the expression "thermal quality" be used to distinguish between thermal quality and skiing quality, for example.

In April and May 1941, the writer, with R. E. LUNDQUIST, J. R. HELLER, and other observers, made about 300 determinations of snow-quality in Utah and Wyoming. The field-work for an observation requires about a half hour, and the computation and checking require an additional 15 minutes. The time plus the equipment necessary make it doubtful if snow-quality determination by quantitative methods will be a routine part of many snow-surveys. However, it is possible to relate snow-quality to the physical appearance and feel of the snow. Good packing-snow, adhesive enough for making snowballs, contains a certain amount of liquid water. If the snow contains less than this optimum amount of water, it packs with difficulty, if at all. If the snow contains more than the necessary quantity of water for making snowballs, various degrees of pressure in the hands will force some of the water to drip from the sample.

As with soil, the larger the grains or crystals, the smaller is the amount of liquid water that may be held by capillary force. Occasionally the outlet from a draining snow-pack may be dammed, thus adding gravity water to the capillary water. Similarly, liquid water may completely fill the voids in a sample of snow which is melting faster than it can drain. In all the tests described in this paper gravity water was permitted to drain from each sample examined. Figure 1 shows the relation between grain-size, wetness of the snow by handling it, and measured quality. Care was taken, in these selected observations, to standardize the "rule-of-thumb" criteria of snow-condition. The coarse snow felt like rock salt. The fine snow had a soft feel, the grains being too small or soft to be felt individually. Medium snow covered an admittedly variable range between these extremes.

Determination of snow-quality at various times and at various points in a snow-pack may show the distribution of water in the snow, movement of water through the snow, and may indicate rates and location of melting. The wettest snow is found at the upper and lower surfaces of a snow-pack. This is thought to result from the fact that most of the melting takes place at the upper surface, and from the accumulation of water at the snow-soil interface because of snow having greater permeability than most soil. Figure 2 shows the relation between quality and the distance of the sample from either the soil-surface or the air, whichever was closer to the sample. This graph is very similar to the two graphs relating quality to the upper and lower surfaces of the snow separately. Figure 2 shows that not once in three hundred some observations did snow have a quality of less than 80 per cent, without being within ten inches of the ground or the air. While this is subject to the influence of varying depths of snow, it is still significant, because about 100 of the observations were made in snow at least 40 inches deep. Apparently shallow snow may have lower average quality than deeper snow. This is to be expected from the decrease in depth of snow as it melts and becomes wetter. Satisfactory measurements of snow-temperature by means of a mercurial thermometer are nearly impossible, because of the great heat-content and conductivity of the thermometer compared with the snow. Snow-quality determinations indicate snow-temperature. Snow-temperature measurements are not necessary when the quality is known, because quality is a direct measure of the heat necessary to melt snow.

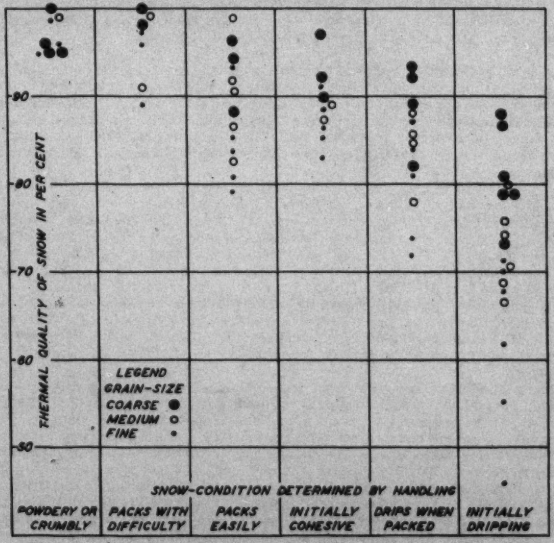

Fig. 1--Relation between measured quality, grain-size, and snow-condition determined by handling

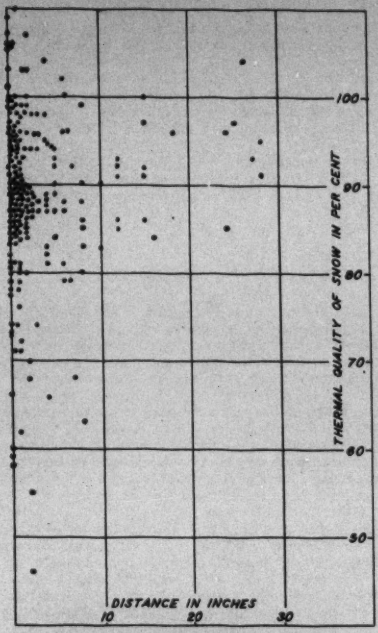

Fig. 2--Relation of snow-quality to distance of sample from soil-surface or air, whichever is closer

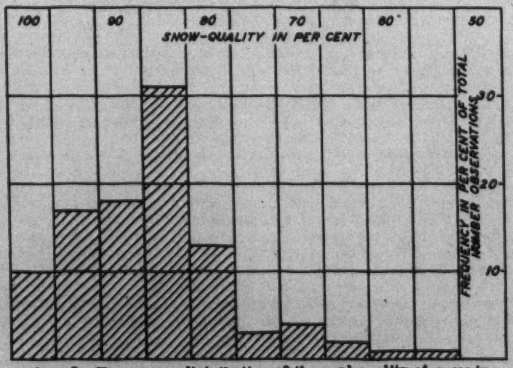

Fig. 3--Frequency-distribution of thermal quality of snow in class-intervals of five per cent

Figure 3 shows the frequency-distribution of snow-quality in class-intervals of five per cent. These observations do not represent a random sample, having a strong bias in favor of low quality because they include many efforts to find lower limits of quality.

Examination has been made of relations between snow-quality and time of day, season, snow-depth, size of sample, exposure to the Sun, and other variables. It is most difficult to interpret the results, because many of the variables are not independent. For example, depth is biased by progress of the melting season, and grain-size is a function of the age of the snow.

Observations of snow-quality indicate not only snow-condition, but also are being used to study sources and rates of heat-transfer, and to locate and trace the movement of water in the snow. The writer hopes that he can report further on these subjects in the near future.

U. S. Weather Bureau,
Washington, D. C.

DISCUSSION

CARROLL F. MERRIAM (Pennsylvania Water and Power Company, Baltimore, Maryland)--It is the duty of the leader of the discussion to point out wherein the paper is incomplete. The primary weakness is that like many investigators this author has given a faithful account of his research, but has not made clear the broader implications and the importance of his work. In other words, he has neglected to place his gem in an appropriate setting.

A few years ago the question of the heat necessary to convert snow-cover into runoff was raised at one of the annual round-table discussions of the Section of Hydrology. Nobody present had any definite experimental knowledge in spite of the fact that the potential danger of exceedingly rapid runoff causing serious floods may be largely affected by this factor. The author is to be congratulated not only in making a serious effort to obtain field-data, but also in taking definite steps to derive usable results of practical value.

It is obvious that tests of this kind cannot be added to the duties of the snow-surveyor without undue encumbrance. However, Figure 1 shows clearly the relation between physical properties of the snow and unusually low values of thermal quality, which in turn must be regarded as a potential threat of floods. It would seem logical, therefore, that if the surveyor could carry out a sufficient number of tests personally on snow within easy reach of a laboratory, he would readily develop a sense of feel which would enable him to give warning of impending danger.

It is furthermore obvious that lighter snow-covers under 20 inches in depth present in proportion to their depths a greater hazard than heavy. Consequently, interest in this subject should be greater along the southern fringe of the snow-cap where the winters are characterized by rapidly disappearing and often broken and intermittent snow-sheets in contrast to the more consistent all-winter cover farther north or high in the mountains.

Now that we are well on the way to recognize the conditions most conducive to floods from the point of view of heat required, we should not forget the other side of the equation, that is, heat supplied. Obviously some thought should now be given to measurements of rain-temperature since the power to supply heat from rain depends directly upon the number of degrees above freezing. Another application for the technique the author has developed is the possibility that careful studies of changes in quality resulting from absorption of heat from various sources, together with radiation to the surroundings, may afford means of measuring heat-transfer rates which have presented difficulties in the past.

Although the Figures indicate that under rather rare circumstances the heat required to melt a snow-cover may be reduced to 50 per cent of that necessary to melt an equivalent weight of ice, it should be pointed out that as yet we do not know to what extent the maximum rate of runoff may be increased under these circumstances. It is possible that the first rainfall is impounded in the icy matrix and then suddenly released giving rise to rate of runoff far exceeding that which could be accounted for by mere addition of snow-melt to precipitation. We do know, however, that sudden melting of snow-cover under warm torrential rains has caused serious floods in the past; to have some means of recognizing in advance the approach of snow-conditions conducive to such catastrophies is to say the least an important advance.

SOME POSSIBLE ERRORS IN SNOW-SAMPLING

C. H. Niederhof and E. G. Dunford

(Abstract)

In 1941, tests were conducted by the Rocky Mountain Forest and Range Experiment Station to determine the possible errors in snow-sampling resulting from the use of inexperienced men and different instruments of the same type.

The conclusions drawn from this study are:

(1) All new survey-crews should be trained carefully in the technique for measuring snow under all expected snow-conditions.

(2) The Utah snow-tube, together with an iso-elastic scale reading to tenths of ounces, is capable of good precision if handled by a well-trained crew. The error of this instrument in sampling snow at a single spot is about ± 0.53 ounce (or about one-half inch of water).

(3) As there may be some variation between individual instruments, it is desirable to use a single instrument for all precise measurements to be compared with each other.

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THE SPACING OF RAIN-GAGES AND THE MEASUREMENT OF FLOOD-PRODUCING RAIN

Katharine Clarke-Hafstad

(Abstract)

A study has been made of the accuracy with which the volumes of rainfall sufficient to cause primary floods on watersheds of the Muskingum Basin, Ohio, can be measured with various networks of rain-gages. The basic rainfall-data used were the four-hourly observations from approximately 400 rain-gages set up on the 8,000 square-mile area of the Muskingum Basin by the Soil Conservation Service. The approximate volumes of rainfall necessary to produce flooding were estimated from unit-hydrographs, rates of discharge at flood-stage, base-flow, and assumed amounts of retention.

The total rainfall for the 12-hour period of maximum intensity for each of 50 rainstorms was assumed to have centered over each of the minor watersheds. The mean depths of rain for each of these 50 periods and for five different spacings of rain-gages were determined for each of the watersheds. No calculations were made for less than three gages on a watershed.

Table 1 gives the area of each of the watersheds, the approximate mean depth of rainfall necessary to produce flooding, the number of 12-hour rainfall-periods out of the 50 studied when this flood-depth was obtained by transposing the storm onto the watershed, and the cases in which and the amount by which the flood-depth would not have been estimated by various spacings of gages.

On the three watersheds of more than 300 square miles the flood-depth was underestimated in only two out of 14 possible cases with fewer than one gage for every 167 square miles of area. On smaller watersheds the flood-depth was more frequently underestimated. The amounts by which the flood-depths were underestimated were large only for the smaller watersheds. The two highest deviations (0.22 inch and 0.19 inch from a flood-depth of 0.87 inch) occurred on Pleasant Hill Watershed (200 square miles) in two summer storms identifiable only as air-mass thundershowers. One of these same storms gave the relatively high deviation of 0.15 inch from a flood-depth of 0.81 inch on Mohicanville Watershed with a spacing of one gage every 90 square miles.

Because of the limited number of storms and the manner in which they were selected, the results of this study indicate only approximately the size of errors involved in determining the mean depth, or the volume, of a flood-producing rain by various spacings of rain-gages.

Table 1--Estimated necessary mean depth (d) of rainfall to produce flooding in Muskingum Basin watersheds, number of times (n) this depth obtained by transposing rainstorms onto watersheds, and number of cases (m) in which this flood-depth would not have been estimated by various average spacings of rain-gages and amounts of underestimate (Δd)

Watershed	Area	d	n	Average spacing in square miles per gage									
				37		90		107		167		300	
				m	Δd	m	Δd	m	Δd	m	Δd	m	Δd
	sq mi	in			in		in		in		in		in
Mohawk	1500	0.93	14	..	.....	1	0.07	..	.....	1	0.03	1	0.01
Dover	1398	1.14	7	..	.....	..	.....	..	.....	..	.....	1	0.01
Wills Creek	844	1.92	3	..	.....	..	.....	..	.....	..	.....	1	0.05
Beach City	300	1.05	19	..	.....	4	0.09	3	0.10	..	.....	..	.....
							0.11		0.03				
							0.01		0.01				
							0.01						
Tippecanoe	286	0.93	26	..	.....	..	.....	1	0.14	..	.....	..	.....
Mohicanville	269	0.81	29	1	0.15	3	0.17	..	.....	..	.....	..	.....
							0.07						
							0.01						
Charles Mill	216	0.99	23	1	0.03	..	.....	..	.....	..	.....	..	.....
Pleasant Hill	200	0.87	31	3	0.22	..	.....	..	.....	..	.....	..	.....
					0.19								
					0.03								
Piedmont	122	0.60	37	2	0.02	..	.....	..	.....	..	.....	..	.....
					0.01								

Soil Conservation Service,
Washington, D. C.

AREAL EXTENT OF INTENSE RAINFALLS, NEW MEXICO AND ARIZONA

Luna B. Leopold

The occurrence of intense rainfall covering relatively small areas is a distinctive feature of summer precipitation in the southwestern States. In the design of engineering structures commanding small watersheds, the chance of experiencing one of these cloudbursts over the drainage-area is one of the governing factors. Owing to the small areal extent of these rainfalls of high intensity and to the long distances between rain-gages, it is seldom that more than one rain-gage is covered and the net result is a dearth of information on the subject of areal pattern.

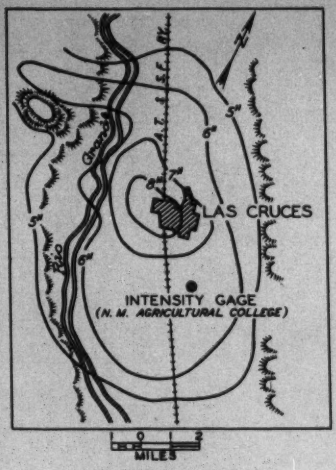
In this discussion, the storms of high intensity rainfall which have been centered over a watershed in such a way as to be diagnostic of the areal extent, are described.

Storm of Las Cruces, New Mexico, August 29-30, 1935--Rainfall measured by the intensity-gage at the New Mexico State Agricultural College just south of the City started at $23^h\ 05^m$, August 29, and had totaled 5.85 inches by $02^h\ 25^m$. The rain in the City was said to have started about $22^h\ 30^m$. Flood-water began flowing into Las Cruces from the mesa east of the City shortly after $01^h\ 00^m$, and a large part of the City was inundated within an hour. Water reached a depth of four feet over a considerable part of the residential district and more than 100 houses were destroyed or damaged.

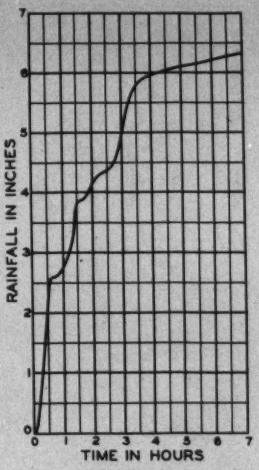
Heavy rains fell during the same night on the watersheds of Santa Teresa Arroyo, Spring Arroyo, and Broad Canyon, all near Hatch, New Mexico, and rains occurred in the Rincon Arroyo Basin. The heaviest storm in the memory of old settlers occurred east of and near the Organ and San Andreas Mountains during the same night.

From investigation of rain-water collected in cans, tubs, and other containers, H. W. YEO [see 1 of "References" at end of paper] constructed a map of the extent of the rainfall which is presented in Figure 1. The recorded rainfall at surrounding stations is shown in Figure 2.

Storm of Parker Creek, Arizona, August 5, 1939--An unusually high rainfall occurred at Parker Creek (Sierra Ancha), the field-post of the Southwestern Forest and Range Experiment Station, 48 miles northeast of Globe, Arizona, August 5, 1939. Due to the concentration of rain-gages at the station, an isohyetal map of the rainfall could be drawn and is presented in Figure 3.



ISOHYETAL MAP



MASS CURVE OF RAINFALL

Fig. 1--Areal extent and intensity of storm-rainfall, August 29-30, 1935

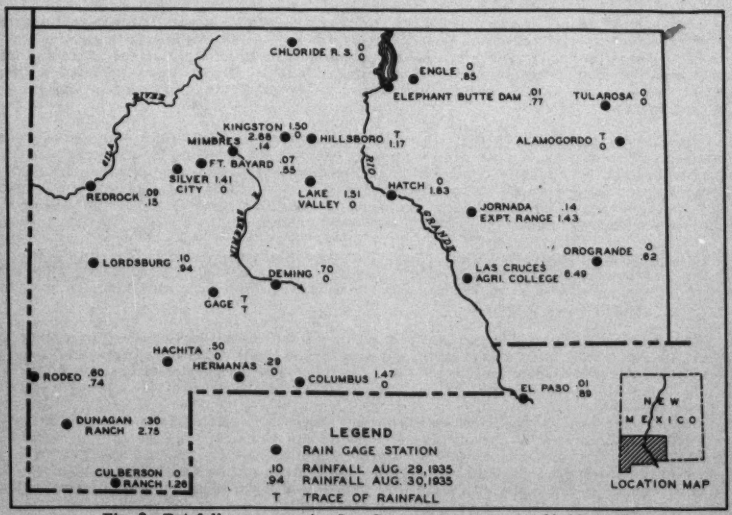
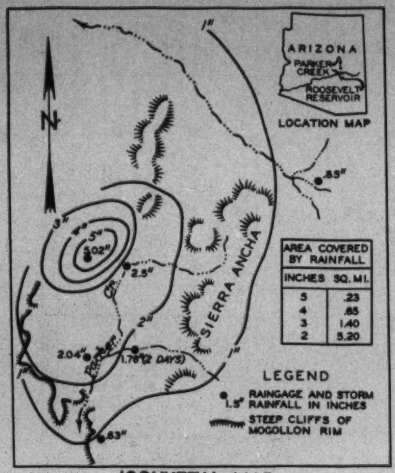


Fig. 2--Rainfall accompanying Las Cruces storm, August 29-30, 1935



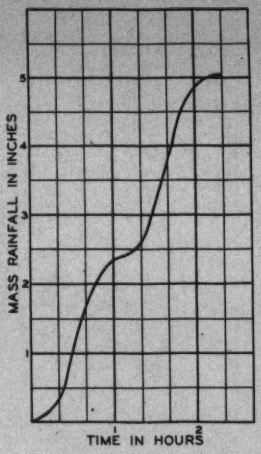


Fig. 3--Storm of August 5, 1939, Parker Creek, Arizona

Storm of Thatcher, Arizona, September, 1939--A high rainfall centered over the numerous rain-gages in the vicinity of Thatcher, Arizona, September 16, 1939. A field-investigation permitted the construction of an isohyetal map, and observations by local people provided some data on storm-movement, particularly time of beginning of rainfall. These data are included in Figure 4. An intensity-gage located about five miles from the storm-center furnished the intensity-pattern presented in Table 1.

Storm of August 12-14, 1940, New Mexico and Arizona--The storm which occurred in southwestern New Mexico and southern Arizona during the afternoon of August 13, 1940, has been described in detail in an excellent report of the United States Engineer Office [2]. Precipitation was general over a large area but the occurrence of very heavy rainfall at high intensity was spotty and confined to relatively small areas. The report of the United States Engineer Office summarized the meteorologic causes of the storm-rainfall as follows:

> "The rainfall apparently was the result of the convergence and weak frontal activity which supplied the necessary 'trigger action' to release the potential energy in the warm air. The resultant convection explains the spotty nature of the rainfall in areas where orographic influence was absent."

There were four widely separated storm-centers in this storm, located near Rodeo (New Mexico), Tumacacori Mountains (Arizona), Tucson (Arizona), and Tombstone (Arizona). The total storm-rainfall at the storm-center was more than four inches near Rodeo, and five inches in the Tumacacori Mountain Area, but in neither of these localities was there an intensity-gage.

Depth-area curves--For the storms described above, sufficiently detailed isohyetal maps are available to warrant the construction of depth-area curves which are presented in Figure 5. In addition, a storm measured at Navajo Experiment Station, Mexican Springs, New Mexico[3], is included. This experimental center of the Soil Conservation Service maintains a large number of standard and recording rain-gages and will in the future provide isohyetal maps of storm-rainfall to greatly augment the data on areal pattern of local storms in the southwest, but unfortunately up to 1940, no very intense rainfalls totalling relatively large amounts of precipitation have occurred over the rain-gages.

Table 1--Rainfall-intensity record at Freeman Flat near Safford, Arizona, September 16, 1939

Time	Minutes, cum.	Inches, cum.	Time-increment	Intensity
h m			min	in/hr
09 48 PM	0	0.00		
			2	3.00
09 50	2	0.10		
			5	2.40
09 55	7	0.30		
			5	1.68
10 00	12	0.44		
			5	2.52
10 05	17	0.65		
			5	2.76
10 10	22	0.88		
			5	1.68
10 15	27	1.02		
			5	1.44
10 20	32	1.14		
			5	0.48
10 25	37	1.18		
			5	2.40
10 30	42	1.38		
			5	2.04
10 35	47	1.55		
			5	1.44
10 40	52	1.67		
			5	0.72
10 45	57	1.73		
			5	0.12
10 50	62	1.74		
			20	0.09
11 10	82	1.77		
			25	0.02
00 35 AM	107	1.78		
			5	0.60
00 40	112	1.83		
			50	0.08
01 30	162	1.90		

The depth-area curves of Figure 5 are approximately parallel with the exception of that curve for the Mexican Springs storm. Due to the exceptionally large number of gages recording the latter storm, the isohyetal pattern is better defined than for the other storms. It may be that the other curves would also tend to flatten toward the left as does the curve for the Mexican Springs storm if the data were more complete. From the few depth-area curves available for this type of storm it appears that for purposes of design, an areal pattern for any storm can be derived if the maximum rainfall at the storm-center is given. This maximum may be determined by drawing rainfall-frequency curves for stations near the watershed under consideration, choosing a value of total rainfall for design purposes. Then a depth-area pattern may be obtained by interpolating a line parallel to the curves presented in Figure 5. Due to the meager data such a depth-area pattern would be a rough approximation which can be improved upon by more records of cloudburst-storms.

Intensity-time patterns for such storms are much better defined than depth-area curves owing to the records of automatic rain-gages which have been in operation in the southwestern States, particularly during the period since 1939. The intensity-time patterns for summer-type, local storms are very similar even for storms occurring in widely separated areas all over New Mexico and Arizona [4]. The highest intensity ordinarily comes at or immediately after the beginning of rainfall and tends to decrease during the storm.

Additional records of areal extent of cloudbursts--In some cases, the discharges from various tributaries of a watershed make it possible to determine approximately the areal extent of an intense storm. For example, on September 20, 1941, a thunder-storm centered over Las Calabacillas Arroyo about eight miles north of Albuquerque, New Mexico. No rain-gages were near the storm-center, but there were sufficient gages near the borders of the storm to show the maximum area covered. The highest precipitation was estimated to be over four inches, most of which fell in less than an hour. The storm covered less than 80 square miles and a peak-discharge of 10,000 cfs

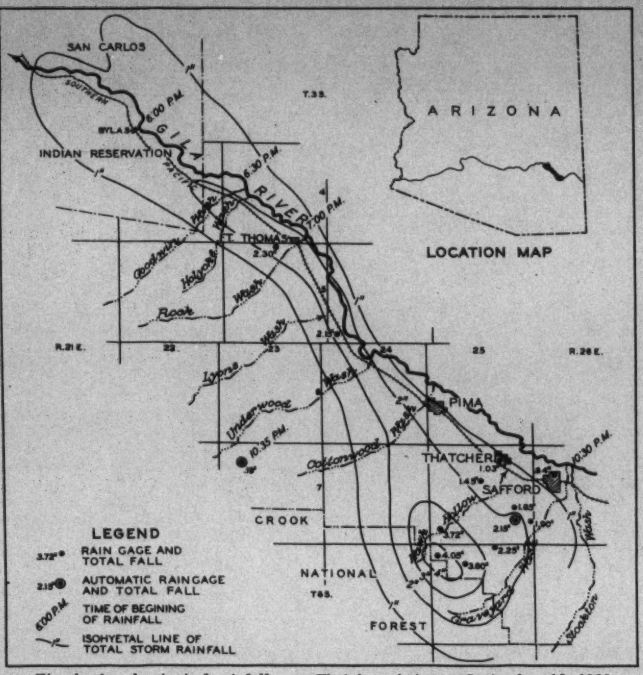


Fig. 4--Areal extent of rainfall near Thatcher, Arizona, September 16, 1939

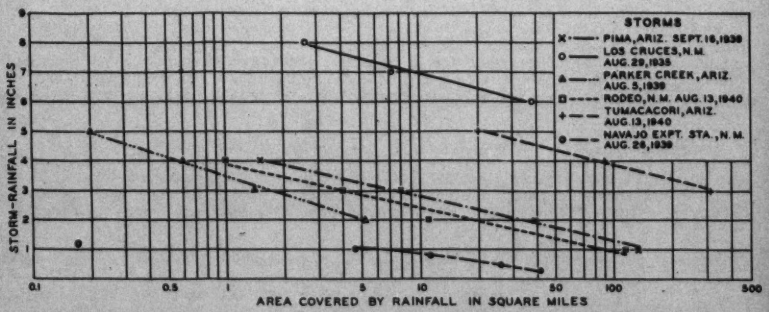


Fig. 5--Depth-area curves for local summer storms, New Mexico and Arizona

was estimated at a point commanding approximately 70 square miles. This flood deposited more than 250 acre-feet of sediment in a fan at the mouth of the wash.

On August 20, 1935, a cloudburst centered over two small ephemeral washes north of Cochiti Pueblo, New Mexico. The peak-discharge was estimated to be 4100 cfs from one wash having a drainage-area of 0.80 square mile and 2000 cfs from the adjacent watershed having a drainage-area of 0.84 square mile [5]. The estimates of flow were made from high-water marks after the flow had ceased and are, therefore, subject to the error inherent in such estimates. The exact areal extent of the heavy rainfall cannot be determined. The nearest rain-gage at Frijoles Canyon, 15 miles north of Cochiti, recorded 2.50 inches on August 20. Alamos Ranch, 20 miles north, recorded 1.46 inches, and Lee Ranch, 15 miles northwest, recorded 1.10 inches. No other stations in the region showed appreciable rainfall. This indicates that an area roughly 20 miles in a north-south direction by 15 miles in an east-west direction received over one inch of rainfall, and the storm-center must have received well over three inches.

Another example of the local nature of the high rainfall of the convective thunder-storms in summer is the rain at Cerro, New Mexico, August 17, 1922. At this station 7.5 inches fell in four hours, yet surrounding stations showed no exceptional precipitation.

Such a rainfall-pattern is common in the Southwest, and, therefore, few heavy rains center over more than one or two rain-gages. Figure 2 shows a typical condition in which one station, Las Cruces, received a heavy rain, 6.49 inches as a total for two days, but most of which fell in three and one-half hours late in the night of August 29. The rainfall-quantities at other stations in the region as shown by Figure 2 indicate the local character of the intense precipitation. To construct an isohyetal map for the whole State for such a storm would be misleading since, owing to the scarcity of gages, the local nature of the storm-centers would be obscured.

Rainfalls lasting over a series of days as in the storms of May 20-28, 1941, in southeastern New Mexico and September 20-24, 1941, in eastern New Mexico, cover much larger areas than the local convective storms discussed in this paper. In general, the intensity of rainfall in the wide-spread storms is not as high as in the local cloudbursts. For small watersheds, the highest discharges result from the local high-intensity storms, and for such occurrences, the depth-area curves presented in this discussion are applicable.

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DISCUSSION

L. L. HARROLD (Soil Conservation Service, Washington, D. C.)--The areal extent of storms, time-area-depth relations, and recurrence-intervals (commonly called "frequency") have been the subject of much discussion. Many have devised frequency-depth relationships for point-rainfall records. Some have applied point-rainfall frequency-depth relationships to large areas. Others have worked entirely with the areal distribution of the storm and its relative position on the area under study. Few have combined recurrence-interval with area and depth of storm.

The author has presented the data for five intense storms in the arid Southwest, including tables, isohyetal maps, and time-depth curves. This in itself is a contribution. He then prepares area-depth curves for each storm and proposes to use these in connection with depth-recurrence-interval curves for rainfall-stations near the watershed under study in order to develop a depth-area pattern.

My discussion is to point out a few reasons for questioning the statement that this procedure provides a means for deriving the areal pattern of any storm. I propose no better method.

In the first place, the isohyetal map may not be a good representation of the areal distribution of rain. True it may be the best available, as there is practically no area in this region with rain-gages so spaced as to give adequate storm-coverage. The nearest to this goal is probably the area on the Navajo Experiment Station, Mexican Springs, New Mexico, where 85 recording rain-gages serve an area of 60 square miles. Even there, the isohyetal lines are not always well established. Seldom is it possible to close more than two or three isohyetal lines for a storm as most of the lines run out of the gaged area, thus preventing the development of area-depth curves. Records of intense summer storms in this area show wide variation between rainfall recorded at adjacent gages 2,000 feet apart, the difference at times amounting to over an inch of rain. The omission or the addition of one gage might greatly change the shape of isohyetal lines.

The isohyetal lines for the storm of September 16, 1939, near Thatcher, Arizona, extend up the Gila River Valley, where there are fewer rain-gages than near Thatcher. I wonder what the shape of the lines would be if the same density of rain-gages as that near Thatcher existed throughout the entire storm-area.

Assuming the correctness of the isohyetal lines and the depth-area curves the author then suggests that the depth-area curve for any intense storm in this area would be roughly parallel to those of the five storms presented. In order to fix the position of the desired depth-area curve a value of total rainfall is chosen from the rainfall-recurrence-interval relations for stations near the watershed. Is this chosen value assumed to be the maximum rainfall at the storm-center? Where on the depth-area chart is this chosen value plotted, that is, what area is it supposed to cover--0.01, 0.1, or 1.0 square mile? These questions must be answered before the position of the area-depth curve is fixed. If the author had given an example of the procedure, these questions would probably have been answered. The essence of the question is: What areal significance can be given to point-rainfall?

If the author assumes that the value chosen from the rainfall-frequency records at the nearby station is the maximum at the storm-center, the resulting area-depth curve would probably be too low (in rainfall-depth) as the probability of any one of the gages in this region being at the storm-center of any storm is rather remote.

The depth-area curve alone is not sufficient in hydrologic studies of watersheds. Such factors as shape of the storm-areas, its position over the watershed, and time-depth relations for various parts of the watershed are also needed.

G. N. BRANCATO (U. S. Weather Bureau, Washington, D. C.)--The isohyetal maps presented by Mr. LEOPOLD of several thunder-storms which produced floods in New Mexico and Arizona are of considerable interest in that they add to our knowledge of the areal extent of some of these storms. However, it is doubtful that the areal extent of intense local storms can be derived from the conclusions reached from a few depth-area curves for this type of storm.

If it could be determined that the isohyetal pattern produced in such a storm was the result of a single thunder-storm, and the speed, diameter, and change of intensity with time of this thunder-storm could be obtained, then it is possible that the areal extent of the intense rainfall could be determined in the manner suggested. In this case it would also be necessary to know that the maximum rainfall at the storm-center had been measured and it is not likely that this could be ascertained by simply drawing rainfall-frequency curves for stations near the watershed as suggested.

Occasionally flash-floods are produced by a single thunder-storm but when conditions are most favorable for the development of intense thunder-storms they most frequently occur in families or groups so that the isohyetal pattern produced over any given area is usually the result of more than one thunder-storm, especially in cases where the duration of heavy rainfall is greater than two or three hours. It can be easily seen that the isohyetal pattern produced by more than one thunder-storm over a given region would vary considerably and could not be determined in the simple manner suggested.

Assuming the suggested method for determining the areal extent of high intensities of rainfall to hold for a single thunder-storm and also that the amount of rainfall at the center can be ascertained, before the areal extent can be derived in the manner suggested it would be necessary to determine what areal significance to give this center, that is, whether it can be considered a point or whether it represents an appreciable area. From a recent study made of several thunder-storm

situations over a dense network of stations in the Muskingum Watershed, Ohio, and from meteorological considerations, there is good reason to believe that over an appreciable area near the center of a thunder-storm the intensity of the rainfall is practically the same. In order to determine the limits of this area it would be necessary to have a dense network of rainfall-recording stations not more than one-quarter mile apart.

It should also be pointed out that only a slight deviation from a curve parallel to those in Figure 5 represents a considerable difference in the area receiving a given amount of rainfall. For example, by making the storm-curve for Parker Creek parallel to that for Rodeo starting with five inches the area receiving two inches of rainfall would be approximately 20 square miles instead of five square miles, an error of approximately 300 per cent. Furthermore, if some of the curves on Figure 5 were extended on the same slope the area receiving over one inch of rainfall would be far in excess of the observed area.

R. S. GOODRIDGE (Soil Conservation Service, Washington, D. C., communicated)--Immediately south of central New Mexico lie the counties of El Paso and Hudspeth in Texas. A study of the rainfall-characteristics of the region required consideration of the rainstorms which are the subject of the author's valuable contribution together with those available to the writer in March 1942.

An inquiry was made of the War Department through its Corps of Engineers for pertinent data of the storms of the region which were applicable. Two sources of such data were suggested; one, the "Supplemental Bulletin of daily and hourly precipitation" for September 20-24, 1941, a product of the Hydrologic Network of the Southwest District by the United States Weather Bureau in cooperation with the War Department, Corps of Engineers, and the Department of Agriculture, Office of Land Use Coordination, and the other, "The preliminary report on the Pecos River and tributaries, Texas and New Mexico, for flood control and allied purposes" in preparation by the Corps of Engineers at the Galveston (Texas) District Office.

This last report set forth the area-depth relations [from data compiled by the District Engineer Office, U. S. Army, Galveston, Texas, with permission to use approved by the Chief of Engineers] for the outstanding storms of July 20-26, 1905, September 14-17, 1919, May 22 to June 4, 1937, May 20-27, 1941, and the storms of September 20-24 and 27-30, 1941. A plotting of these storms is shown on Figure A together with those considered pertinent from Figure 5 of the author.

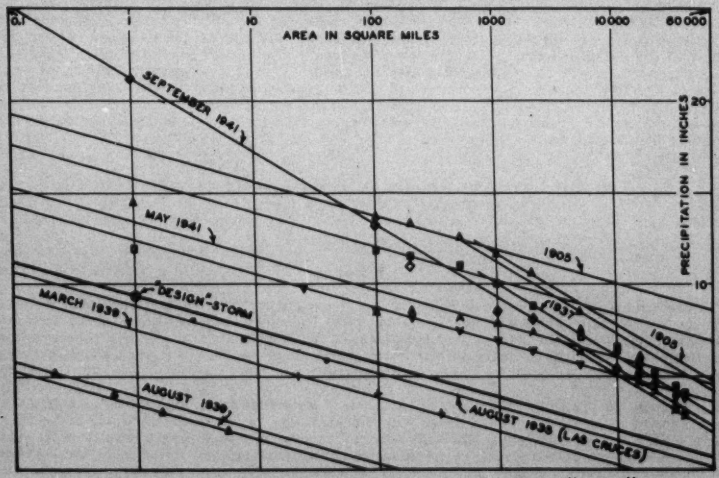

Fig. A--Area-depth curves of precipitation, El Paso - Hudspeth (Texas) ["Design"-storm, shown by heavy line, $y = 210{,}000 \times 10^{-0.5742x}$ and $y = 210{,}000 \times e^{-1.322x}$]

The writer was impressed by the degree to which the curves obtained from War Department data enveloped those of the author yet seemed to have the same alignment-characteristics. The alignment is faithfully sustained by the data for the storm of September, 1919, and seems adaptable to the storm-data for May, 1941, May to June, 1937, and July, 1905, if the hydrologist recognizes that the value for the term "center", which was plotted arbitrarily at one square mile, could be the indicated value for a considerably larger area toward the next designated series for 100 square miles.

The equation indicated from the combined plotted data of Figure A for a selected "design"-storm for minor runoff-structures is shown in both the Briggsian and Napierian systems. The equations are

$$y = 210{,}000 \times 10^{-0.5742\,x} \quad \text{and} \quad y = 210{,}000 \times e^{-1.322\,x}$$

where y = area in square miles and x = depth of rain in inches.

The storm of May 20-27, 1941, appears to take the equations

$$y = 235{,}000 \times 10^{-0.2535\,x} \quad \text{and} \quad y = 235{,}000 \times e^{-0.584\,x}$$

During this storm, however, there are values of area-depths between 5,000 and 20,000 square miles which lie outside or above the bounds of this curve but conform to the bounds of the equation of the storm of July 20-26, 1905, whose equations are

$$y = 85 \times 10^{8} \times 10^{-0.5742\,x} \quad \text{or} \quad y = 85 \times 10^{8} \times e^{-1.322\,x} \quad \text{(to about 900 square miles)}$$

and

$$y = 200{,}000 \times 10^{-0.1878\,x} \quad \text{or} \quad y = 200{,}000 \times e^{-0.4325\,x} \quad \text{(for areas greater than about 900 square miles)}$$

The constants, 200,000 to 235,000, conform closely to the extent in square miles of the storms reviewed by the Miami Conservancy District in "Storm rainfall of Eastern United States" (1936) and the Ohio and Mississippi River floods of 1937 in the Geological Survey Water-Supply Paper 838, 1938.

In summary, the curves of Figure A of this discussion indicate depths about two and one-half times as great with an areal extent increase of the same magnitude if one will consider that the curve for the storm of Las Cruces, New Mexico, August 29, 1935, could be extrapolated theoretically to represent the possible characteristic of a potential storm in the region. On the other hand, quantitative data from the United States Engineer Offices extend the areal scale to about 100 times, the ratio of the 310 ∓ square miles of the author's curves to the 35,000 + of the curve-data of the United States Engineers.

THE INTERCEPTION OF RAIN AND SNOW BY A FOREST OF YOUNG PONDEROSA-PINE

W. M. Johnson

Introduction

The interception of rain and snow by the forest-canopy is a factor of sufficient magnitude to require its measurement in any complete study of the hydrology of forested watersheds. In experiments set up to measure the relations of watershed-runoff and infiltration to precipitation it is particularly essential to measure net rainfall reaching the soil under the forest-canopy, rather than total precipitation, in order to estimate adequately the amounts of water available for runoff.

The study described in this paper is one phase of watershed-management studies conducted by the Rocky Mountain Forest and Range Experiment Station, in cooperation with the Colorado State College of Agriculture and Mechanic Arts, in the ponderosa-pine type of Colorado. It was designed to determine the amount of precipitation actually reaching the forest-floor under stands of immature ponderosa-pine on small watershed-areas, in order that the amount of water lost by interception might be evaluated and that watershed infiltration-capacities under natural conditions of rainfall might be accurately determined. The study deals with amounts of net precipitation

derived from both summer rainfall and winter snowfall but ignores the amount of water reaching the ground as stemflow. Present incomplete studies indicate that stemflow is of minor importance in a stand of immature ponderosa-pine.

Rainfall-interception has been studied by many investigators but no work has been done in the ponderosa-pine type characteristic of the Front Range of the Colorado Rockies. WILM and NIEDERHOF [see 7 of "References" at end of paper] have studied the problem in the lodgepole-pine type in Colorado, finding that under virgin stands approximately 30 per cent of the summer rainfall was intercepted and that by timber-cutting this amount was decreased to as little as eight to ten per cent. DE FOREST [1] found that both herbaceous and tree cover intercept large quantities of rainfall and that the amount depends upon the amount and intensity of the rainfall. ZON [9], HORTON [2], KITTREDGE [4], WICHT [6], and others have also contributed to the general knowledge of rainfall-interception.

Experimental procedure

This experiment was conducted on the upper South Platte River Watershed, in an area typical of the ponderosa-pine type of the Colorado Front Range. Here 70 to 80 per cent of the annual precipitation falls in the form of rain, largely in small showers interspersed with occasional storms of high intensity. In this area six watersheds, supporting stands of immature ponderosa-pine, are being studied to learn the influence of forest-management on surface-runoff, infiltration, and erosion.

Three of the watersheds were used for this study of interception. In each watershed six standard rain-gages were located under tree-crowns and six in large openings near each of the interception-gages. The location of each gage was determined by random selection from all available locations in openings and under the forest-canopy. The study was started in July, 1940, and continued until October, 1941. Whenever possible rainfall was measured after each storm; observations were recorded in inches of water.

The study was designed for analysis by the covariance-method as outlined by SNEDECOR [5]. In one phase of the analysis only seasonal total gross and net rainfall were used to learn whether net rainfall differed between watersheds or between seasons. The results were divided into three six-month periods, roughly including the seasons characterized by either rain or snow, namely, the summer periods of 1940 and 1941 (April through September), and the winter of 1940-41 (October through March). In a second phase of the analysis 13 storms were selected at random from the total available storms for each season. As this analysis was made primarily to determine the relation between gross and net rainfall for individual storms it was necessary to eliminate all observations which included more than one storm. During the summer season of 1940 only 13 storms met this requirement, so the same number of storms was selected from each of the other two seasons.

In both sets of covariance-calculations, the purpose of analysis was only to learn whether the adjusted net rainfall varied among the three watersheds, and whether there was a significant variation between seasons. No attempt can be made to estimate interception-effects in other watersheds, since the areas studied are by no means a random sample of the entire ponderosa-pine type. Accordingly the variance within watersheds was the appropriate error term for testing the comparison between watersheds; and the interaction of "season" and "within watersheds" was used for testing the comparison between seasons and the interaction of watersheds and seasons.

Results

Seasonal total gross and net rainfall--During the course of the study 140 storms occurred which were used to make up the seasonal totals of gross and net rainfall (Table 1). These data show that by far the greatest number of storms occurred during the summer season of 1941. In general, rainfall in the summer of 1940 was approximately average in amount and character, followed by a rather dry and open winter; and the summer season of 1941 was above average in both number of storms and amount of rainfall. With approximately the same total precipitation on all watersheds, there was over three inches more net precipitation on watershed "B" than occurred on the other two areas. Averaging the three watersheds, 81.4 per cent of the total precipitation reached the ground under the forest-canopy.

Although net precipitation varied greatly among the three seasons, analysis of covariance (Table 2) showed that this fluctuation was entirely a function of gross precipitation; no significant difference remained between seasons after adjustment to the average gross precipitation

Table 1--Total seasonal gross and net rainfall by watersheds

Season	Number of storms	Watersheds						Average		
		B		C		E				
		Gross	Net	Gross	Net	Gross	Net	Gross	Net	Per cent[b]
		in	in	in	in	in	in	in	in	
Summer, 1940	25	4.61[a]	3.89	4.54	3.66	4.81	3.79	4.65	3.78	81.3
Winter, 1940-41	27	2.68	2.07	2.77	1.92	2.93	1.87	2.79	1.95	69.9
Summer, 1941	88	15.38	14.98	15.89	12.14	14.98	11.53	15.42	12.88	83.5

[a]Each entry is the average of records at six gages.

[b]Net precipitation expressed as percentage of gross.

Table 2--Covariance analysis of total seasonal net rainfall

Source	(D/F)	r^2	Mean square (errors of estimate)
Total	52	0.9214	2.0313
Between means of			
(1) Watersheds	2	.....	8.8974[a]
(2) Seasons	2	.....	0.2441
Interaction (1) × (2)	4	.....	5.7390[b]
(3) Within watersheds (error for watersheds)	14	0.0526	2.2433
Interaction (2) × (3) [Error for seasons and (1) × (2) interaction]	29	0.0816	1.1088

[a]Significant ($p. < 0.05$). [b]Highly significant ($p. < 0.01$).

Table 3--Covariance analysis of net rainfall in individual storms (for determination of errors)

Source	(D/F)	r^2	Mean square
Between means of			
(1) Watersheds	2	.....	0.1278
(2) Seasons	2	.....	0.0198
Interaction (1) × (2)	4	.....	0.0197[a]
Between locations within watersheds[b]	14	.....	0.0497
Interaction (seasons × locations[c] within watersheds)	29	.....	0.0072
Between storms within locations and seasons	647	0.8598	0.0155

Regression-formulas for each watershed:

Watershed "B" - E = 1.2478x - 0.0626; $r^2 = 0.8804$
"C" - E = 0.9379x - 0.0423; $r^2 = 0.9622$
"E" - E = 0.8879x - 0.0217; $r^2 = 0.9241$

[a]Significant ($p. < 0.05$). [b]Error for testing "watersheds". [c]Error for testing "seasons", "watersheds × seasons", and "locations within watersheds".

(F = (0.2441/1.1088) = less than unity). The excess of net precipitation for watershed "B" over the other watersheds was significant; also, the three watersheds seemed to respond differently to the same total rainfall in different seasons, as indicated by the significant interaction of watersheds with seasons.

Gross and net rainfall from individual storms--The effect of gross rainfall per storm on the amount actually reaching the forest-floor under a crown-canopy was determined on the basis of 13 storms selected at random from each of the three seasons. Analysis of these data (Table 3) reveals the degree of this association and provides a regression-formula for each watershed, from which net rainfall can be predicted for storms of various sizes.

As compared to the analysis of seasonal totals, the adjusted variance between seasons was not quite significant, and the watersheds did not differ significantly. The interaction of watersheds and seasons was barely significant. The results of both analyses indicate that there may be some real variation in net rainfall between watersheds, perhaps because of differences in the forest-canopy. Thus it would not be safe to use the average of the rain-gages in all three watersheds, or to use a single regression-formula, in computing the average net rainfall on a single watershed in any given storm.

The net rainfall on each watershed in single storms can be computed from the regression-formulas in Table 3. By inspection of these formulas it can be seen that the initial storage of the forest-canopy on these watersheds is about 0.03 to 0.05 inch, and that after the crowns have been saturated by initial storage practically all of the rainfall reaches the ground.

Conclusions

The following summarized conclusions can be drawn from the results of this experiment:

(1) On these watersheds an average of 81.4 per cent of the total precipitation reached the ground under tree-crowns. This amount varied significantly among the watersheds, probably because of a variation in density of the crown-canopies.

(2) About 0.03 to 0.05 inch of precipitation is required to saturate the forest-canopy in each storm. After this initial storage is filled, practically all of the rainfall reaches the ground.

(3) After adjustment to values expected for the average gross precipitation, there was no significant difference in net precipitation among the three seasons studied. Apparently the interception of snow by tree-crowns is quite similar in magnitude to the interception of rain; at least in this cover-type and climate.

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DISCUSSION

H. F. MOREY (Allegheny Forest Experiment Station, U. S. Forest Service, Philadelphia, Pennsylvania; communicated)--This paper is a contribution to hydrological knowledge in that it shows that the interception of precipitation may vary within watersheds of the same cover-type. The author states that this may be due to "variation in density of the crown-canopies." No doubt he will investigate the crown-densities of the three watersheds so as to check the assumption of crown-density variance.

Observations made by the discusser during April, 1942, in central Vermont indicate that a correlation may exist between the degree of interception and crown-density, stem-density, and stem-size. Coniferous stands above sapling-size that are very dense generally have thin crown-canopies, although the canopy may be complete. On the other hand, stands of the same species and size that are less dense may have a thick as well as a complete crown-canopy. There appears to be more snow-interception in the latter than in the former stands. Even small holes in the canopy will allow a greater accumulation of snow within the stand than a solid canopy. It has been observed that dense stands of hardwood-reproduction of three inches or less in diameter intercept less snow than stands in which the individuals are larger. The degree of interception also depends upon the understory. If shrubs are present within the stand, or a two-story forest exists, the degree of interception will be greater than if the stand has but a single story. Each type of vegetal cover appears to be limited as to the amount of precipitation it can intercept. Heavy accumulations of snow are blown off more readily than light ones. On the other hand, wet snow sticks better than dry snow, and sleet adheres better than rain. Due to these conditions, a straight

percentage-factor cannot be applied with a high degree of accuracy for the determination of the amount of interception. Each type of storm should be treated individually and should not be grouped.

The author's figures of 0.03- to 0.05-inch interception per storm are believed to be too conservative for snow in the Upper Connecticut Valley. The interception--measured after the snow had blown from the crowns--during a storm which occurred on April 11, 1942, in Central Vermont was 0.08 and 0.36 inch of water, respectively, in fully stocked 60-year northern hardwood and 30-year red-spruce. The amount of water which fell in the open was 0.82 inch. The interception for fully stocked pine of similar size would have been somewhere between that of the spruce and hardwood.

SIMPLIFIED METHOD OF DETERMINING AN INFILTRATION-CAPACITY CURVE FROM AN INFILTROMETER-EXPERIMENT

Robert E. Horton

Notation--
δ_a = average depth of surface-detention, including depression-storage, inches on the plat-area
δ_n = average net depth of surface-detention, excluding depression-storage, inches on area
f = infiltration-capacity, inches per hour
i = rain-intensity, inches per hour
q_s = runoff-intensity, inches per hour
t = duration of rainfall, hours
t_r = duration of residual runoff, hours
V_d = depression-storage, inches depth

The (i - q)-curve--The mass-line method of determining the points on an f-curve--for the sake of simplicity an infiltration-capacity curve is here described as an "f-curve"--developed by the author [see 1, 2 of "References" at end of paper] and heretofore used in the analysis of several series of infiltrometer-experiments, is simple in principle and gives accurate results. Its application is, however, laborious and somewhat involved and there seems to be a reluctance toward using it on the part of some soil-technologists and others. This reluctance may not arise from a desire to avoid labor but from the fact that calculations of f by this method are of the nature of hydraulic or hydrologic calculations, and consequently unfamiliar. This unfamiliarity with fundamental physical and hydrologic laws and processes is revealed by the substitution in some cases of what is called an "(i - q)-curve," which represents the result of subtracting surface-runoff intensities q_s, as determined by infiltrometer-tests, from the corresponding rain-intensity i, and plotting the results in terms of time. The resulting curve is sometimes labeled "infiltration-capacity", which it is not. Whether so labeled or not, it is often used as if it was identical or sensibly identical with a true f-curve.

From the fundamental law of continuity of physics, commonly called in hydrology the storage-equation, $(i - q_s) = (f + d\delta_a)$.

The storage-equation gives

$$(dP/dt) - (dQ_s/dt) = (dF/dt) + (d\delta_a/dt) \qquad (1)$$

where P, Q_s, and F are, respectively, the total rainfall, surface-runoff, and infiltration, for a time-interval t. The four items of this equation represent, respectively, rates of rainfall, surface-runoff, infiltration, and change of storage or surface-detention. Letting i, q_s, f, and $d\delta_a$ represent these rates,

$$(i - q_s) = (f + d\delta_a) \qquad (2)$$

It will be seen at once that what the (i - q)-curve really represents is the infiltration-capacity f plus the rate of increase of surface-detention. The assumption that (i - q) is sensibly the same as f is, therefore, equivalent to assuming the miracle of surface-runoff occurring at a rate q_s with zero-depth of surface-detention to produce it. Actually while the net depth δ_n of surface-detention in cases of small depression-storage V_d may be comparatively small--commonly of the order of 0.1 inch or less on an infiltrometer-plat--the rate of accumulation of surface-detention is not necessarily small--in fact, at the very beginning of runoff it is equal to (i - f). For example, if i = 1.5 inches per hour (iph), which is about as small a value of i as is commonly used

in infiltrometer-experiments, and if at the beginning of runoff, f = 1 iph, then $(d\delta_a/dt) = 0.50$ iph. The value of (i - q) is in this case 1.00 iph, and if this is taken as f, an error of 0.5 iph or 33-1/3 per cent results. It is only when runoff and infiltration-capacity have become constant that (i - q) becomes equal to f.

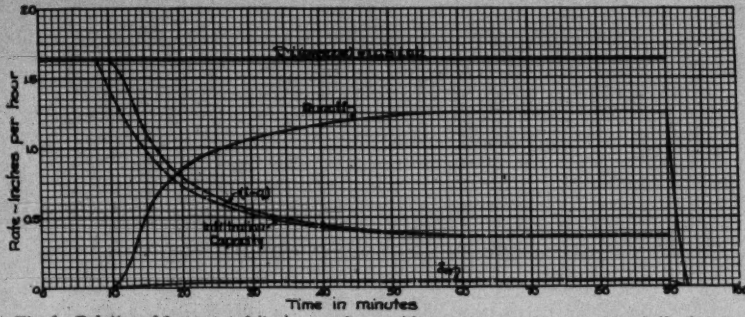


Fig. 1--Relation of f-curve and (i-q) curve from infiltrometer experiment on Marshall silt loam, bare cultivated (data from Duley and Kelly, Circular 608, U.S.D.A., Fig. 3, p. 4)

Two examples of the difference between (i - q)-curves and true f-curves are shown by Figures 1 and 2. In these two cases the maximum differences between (i - q) and the true f-curve at the beginning of runoff are, respectively, 0.28 iph or 28 per cent on Figure 1, and 1.10 iph or 55 per cent on Figure 2. The differences decrease to zero at the time t_c at which the infiltration-capacity becomes constant. These and numerous other examples show that the use of (i - q) as if it represented infiltration-capacity leads to values of f in excess of the true values in the early stages of runoff commonly ranging from 25 to 50 per cent.

Simplified method of deriving an f-curve--The (i - q)-curve cannot be substituted for the f-curve if anything like reasonable accuracy is to be attained. The (i - q)-curve may, however, serve a useful purpose in conjunction with the residual-runoff graph of an infiltrometer-experiment in deriving the f-curve directly in a simple manner.

As elsewhere shown [3], during residual runoff, infiltration takes place at capacity-rate f from a part of the area, decreasing from the whole area at the start, to zero at the end of residual runoff, in such a manner that the average area from which infiltration occurs during the residual-runoff interval t_r is ordinarily about one-third the total area, or the total infiltration during residual runoff is

$$F_r = ft_r/3 \qquad (3)$$

In this equation f is the infiltration-capacity at the beginning of residual runoff, and in case the experiment lasts long enough so that f becomes equal to f_c, the latter is used.

Referring to Figure 3, the residual runoff Q_r is the area oab. If the rainfall had ended at the time t, then the residual-runoff graph would be the arc p'b of the actual residual-runoff graph transferred to cd. Both the residual runoff and residual infiltration are derived from the net surface-detention remaining on the ground at the end of rainfall. The water in depressions enters the soil as infiltration after runoff ends and need not be considered here.

The net surface-detention at the end of rainfall is

$$\delta_n = Q_r + F_r \qquad (4)$$

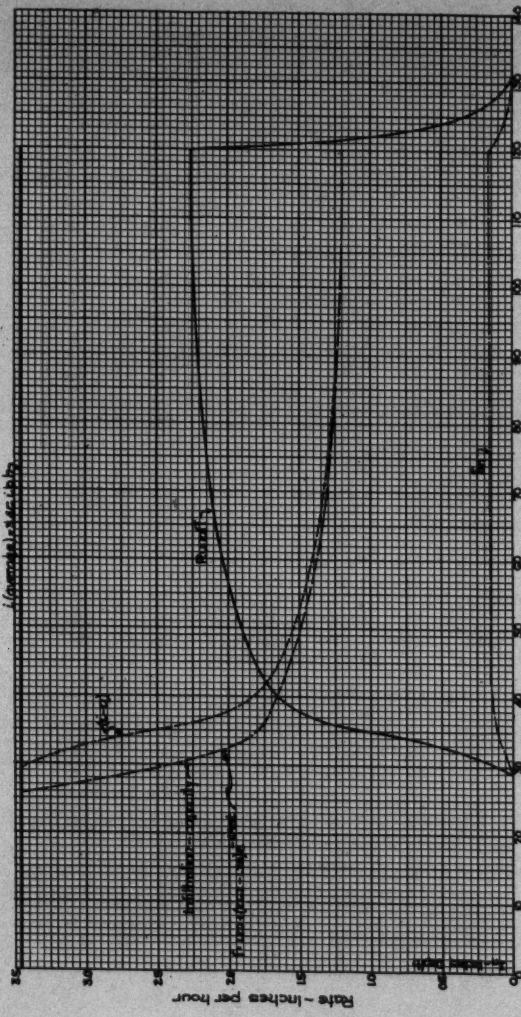


Fig. 2--Relation of f-curve and (I-Q) curve from infiltrometer experiment on Marshall silt loam with straw cover (data from Duley and Kelly, Circular 608, U.S.D.A., Fig. 5, p. 6)

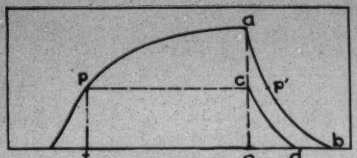
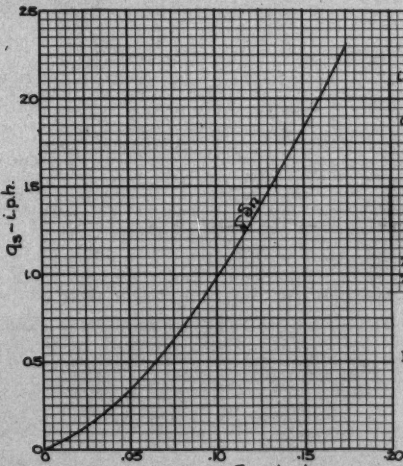


Fig. 3--Residual runoff-graph for rain ending at different times

Since the (i - q)-curve represents values of $(f + d\delta_n)$, values of f can be obtained by computing a series of values of δ_n by means of equation (4), obtaining graphically the corresponding values of $d\delta_n$, and subtracting these quantities from the ordinates of the (i - q)-curve. The best procedure is to first determine a relation-line between δ_n and q_s in the following manner.

Starting at any time t after runoff begins, project the point p on the runoff-curve horizontally to p' on the residual-runoff curve, Figure 3. Determine the area ocd under the residual-runoff graph (arc p'b = arc cd) This expressed in inches depth, is Q_r as it would have been if rain had ended at t. Also compute the value of F_r for the time-interval t_r = od, t_r corresponding to time t, by means of equation (3) and find the value of δ_n by means of equation (4). A series of values of δ_n so derived can be platted in terms of the corresponding values of q_s, thus deriving a relation-curve between δ_n and q_s.

Then taking off from the hydrograph the values of q_s at the ends of successive time-intervals (t - t'), (t' - t"), and so on, and tabulating opposite these the corresponding values of δ_n derived from the relation-curve described, a basis is obtained for evaluating $d\delta_n$. Values of $d\delta_n$, in inches per hour, are obtained by subtracting the value of δ_n at the beginning of any time-interval from its value at the end of the same time-interval and multiplying this by the factor 1/Δt; the products represent approximately the values of $d\delta_n$ at the mid-points of successive time-intervals. These values subtracted from the values of (i - q) at the corresponding times give a series of ordinates of the true f-curve. The computations and graphs used in deriving the f-curve on Figure 2 in this manner are shown on Figure 4 and Table 1. The inserted table on Figure 4 gives details of the



t_r=1.20

q_s i.p.h.	t_r min.	t_r hrs.	$\frac{1}{\Delta t}$ hrs.	F_r ins.	Q_r ins.	δ_n ins.
(1)	(2)	(3)	(4)	(5)	(6)	(7)
0.10	2.7	.045	.015	.015	.0015	.0120
.30	5.4	.090	.030	.030	.0105	.0495
.50	6.9	.115	.038	.045C	.0195	.0655
.70	7.9	.132	.044	.0528	.0290	.0848
1.00	8.8	.147	.049	.0588	.0425	.1013
1.25	9.4	.157	.052	.0624	.0538	.1162
1.50	9.9	.165	.055	.0660	.0650	.1310
1.75	10.2	.170	.057	.0684	.0768	.1452
2.00	10.5	.175	.058	.0701	.0886	.1587
2.27	11.0	.183	.061	.0732	.1005	.1737

Fig. 4--Relation between δ_n and q_s for Marshall silt loam with straw cover for experiment shown on Figure 2

computation of the relation-curve of q_s to δ_n. Columns (2), (3), (4), (5), and (6) contain details of computation of F_r and Q_r for different values of q_s taken from the hydrograph. The corresponding values of $\delta_n = (F_r + Q_r)$ are given in Column (7) and these values platted in terms of q_s are shown by the δ_n-line on the diagram.

Table 1--Computation of f-curve

[Data from Duley and Kelly (Circ. 608, U. S Dept. Agric., Fig. 5, p. 6)]

Time, t (1)	q_s (2)	δ_n (3)	$\Delta S_n \times (60/t)$ (4)	Mean (i - q) (5)	f (6)	Mid-point, t (7)
min	iph	in	iph	iph	(5) - (4)	min
0	0	0	0	.....	.....	.....
29[a]	0	0	0	.....	.....	.....
32.5	0.44	.060	1.030	3.30	2.27	30.75
35	0.98	.100	.960	2.77	1.81	33.75
37.5	1.47	.129	.696	2.20	1.50	36.25
40	1.65	.140	.264	1.90	1.64	38.75
42.5	1.75	.145	.120	1.77	1.65	41.25
45	1.81	.148	.072	1.68	1.61	43.75
47.5	1.86	.151	.072	1.63	1.56	46.25
50	1.90	.154	.072	1.57	1.50	48.75
55	1.98	.158	.048	1.51	1.46	52.50
60	2.04	.161	.036	1.44	1.40	57.50
65	2.08	.163	.024	1.39	1.37	62.50
70	2.12	.166	.036	1.35	1.31	67.50
80	2.18	.168	.012	1.30	1.29	75.
90	2.22	.170	.012	1.26	1.25	85.
100	2.24	.171	.006	1.23	1.22	95.
110	2.27	.173	.012	1.21	1.20	105.
120[b]	2.27	.173	0	1.20	1.20	115.
131[c]	0					

[a]Runoff began. [b]Application ended. [c]Runoff ended.

Details of computation of the f-curve are shown on Table 1. The value of q_s from the hydrograph at the end of each time-interval shown in Column (1) is given in Column (2). The corresponding δ_n read from Figure 4 is given in Column (3). Then δ_n, which is the increment of δ_n for a unit time-interval, is obtained by subtracting δ_n on the preceding line from that on a given line and multiplying by (60/t), where t is the time-interval in minutes. This gives δ_n in inches per hour at a time corresponding to the mid-point of the given time-increment. In this case i = 3.44 iph and the mean (i - q) for the time-increment, Column (5), is obtained either from the (i - q)-curve or computed from i and from the values of q_s in Column (2), Table 1. The values of Δ_n, Column (4), subtracted from the corresponding values of (i - q), Column (5), give values of f at the mid-points of the respective time-increments or at the time shown in Column (7). The f-curve platted from these points is shown on Figure 2 and its equation given.

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[1] ROBERT E. HORTON, Surface runoff phenomena, Publ. 101, Horton Hydro. Lab., Voorheesville, New York, February 1, 1935.

[2] ROBERT E. HORTON, Derivation of infiltration-capacity curve from infiltrometer experiments; Off. Land Use Coord., Flood Control, U. S. Dept. Agric., Washington, January, 1942.

[3] ROBERT E. HORTON, Analysis of runoff-plat experiments with varying infiltration-capacity, Trans. Amer. Geophys. Union, 1939, pp. 693-711.

Voorheesville, New York

DISCUSSION

R. A. HERTZLER (U. S. Forest Service, Washington, D. C.)--Dr. HORTON has presented a simplified useful method of deriving infiltration-capacity curves from infiltrometer-data. It should be emphasized that (i - q)-curves are different from f-curves and that the use of (i - q)-curves to calculate surface-runoff is basically incorrect. The errors in surface-runoff due to the

misuse of (i - q)-curves will be relatively large or insignificant depending upon the shape of the curve and the rainfall-pattern to which it is applied. In calculating runoff from either (i - q)- or f-curves the placement of the curve upon the rainfall-rate diagram may result in larger errors than those inherent in the approximate curves.

To calculate runoff accurately by any method is a complex, time-consuming job and the utilization of infiltrometer-data as an independent measurement of surface-runoff adds to the complexity of the calculations, but pays dividends in increased accuracy. Some time ago we analyzed a series of infiltrometer-experiments and our reluctance to using Dr. HORTON'S mass-line method as described in another publication was due to the amount of work required. To reduce the work, L. K. REINECKE modified this method and developed a procedure similar to that presented this morning. This experience with similar computations shows that Dr. HORTON'S simplified method is adaptable to "mass-production" determinations by relatively unskilled workers, and that it gives good results.

Dr. HORTON'S analysis of the phenomenon of infiltration is logical and is in accordance with field-observations obtained during a large number of actual tests. His method for determining infiltration-capacity curves involves two approximations. The first, substituting the f_c-rate in the equation $F_r = (f\ t_r/3)$, introduces an error in the subsequent calculation of δ_n, but as the differential, $d\delta_n$, is used to determine f this error nearly cancels and the resulting f-rates are substantially the same as those derived by using the calculated f, in place of f_c. This can be verified by treating the f-curve as a first approximation, reading from it the f for the given time, and inserting this rate in the member $(f\ t_r/3)$.

The second approximation, using δ_a and δ_n more or less interchangeably, ordinarily introduces no error because the depression-storage usually is about the same at the beginning of runoff as it is at the end of rainfall. This being true, depression-storage is the same on the rising and falling side of the hydrograph. There are frequent infiltrometer-tests, however, for which these depths are different. The large volume of depression-storage on irregular ground-surfaces such as exist under forest-cover may be so distributed that most of it occurs on the upper end of the plat. Under these conditions the storage-values calculated for the rising side of the hydrograph are inaccurate.

These two approximations, namely, the use of f_c and the substitution of δ_n for δ_a, cause a scatter of the derived points for the early part of the infiltration-capacity curve. The scatter reduces with increasing time so that a smooth curve, drawn through the points that do fall in line, can be extended backward through the scattered points to define an accurate infiltration-capacity curve.

We must realize that the storage-volumes on the plats have been derived in the past from measurements of rainfall and runoff only, and that an independent measurement of these volumes would extend our knowledge of infiltration-capacity. Research along this line is needed for a more thorough understanding of infiltrometer-data and data from small runoff-plats so that these may be applied more frequently in independent calculations of surface-runoff as a part of total runoff.

A SIMPLIFIED METHOD OF DETERMINING THE CONSTANTS IN THE INFILTRATION-CAPACITY EQUATION

Robert E. Horton

Elsewhere [see 1 of "References" at end of paper] the author has given a method for determining the infiltration-capacity curve or f-curve from an infiltrometer-experiment with constant rain-intensity, and has also shown [2] that such infiltration-capacity curves can be represented accurately by the equation

$$f = f_c + (f_0 - f_c)\, e^{-K_f t} \qquad (1)$$

where f_0 = initial infiltration-capacity in inches per hour, f_c = final, constant infiltration-capacity in inches per hour, f = infiltration-capacity in inches per hour at time t in hours, and K_f is a factor which determines the rate of change of infiltration-capacity during rain. This equation expresses the march of infiltration-capacity during rain, for a given rain-intensity and drop-size, in terms of the three constants f_0, f_c, and K_f.

There is another important constant, t_c, which expresses the time in hours required for

infiltration-capacity to drop from its initial value, f_0, to within one per cent of its constant or asymptotic value, f_c. The value of t_c is given by the equation

$$t_c = (1/K_f) \log_e [100 (f_0 - f_c)/f_c] \quad (2)$$

The values of f_0 and f_c are derived directly from the infiltration-capacity curve.

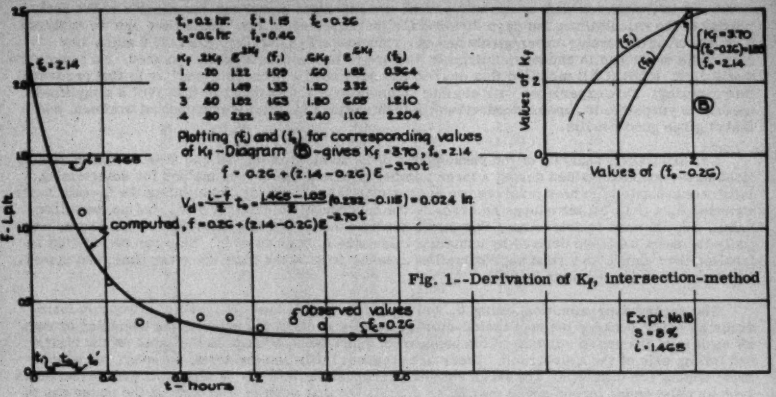
Plotting (f) and (f_a) for corresponding values of K_f - Diagram (B) - gives K_f = 3.70, f_a = 2.14
f = 0.26 + (2.14 - 0.26) e^-3.70t
V_d = ((i-f)/K_f) t_e = ((1.465 - 1.05)/3.70)(0.232 - 0.115) = 0.024 in.
computed, f = 0.26 + (2.14 - 0.26) e^-3.70t
Observed values
f_c = 0.26
Expt No 18
S = 8%
i = 1.465
f - Inches
t - hours
Values of K_f
Values of (f_a - 0.26)

Fig. 1--Derivation of K_f, intersection-method

Heretofore two methods have been developed for determining K_f, namely, the method of intersections and the logarithmic method [3]. Figure 1 is an example of an f-curve and its equation derived by the intersection-method. Both these methods of determining K_f, while accurate, are somewhat involved and laborious.

A third method, that of taking the approximate value of t_c directly from the f-curve and then computing K_f from equation (3) derived from (2),

$$K_f = (1/t_c) \log_e [100 (f_0 - f_c)/f_c] \quad (3)$$

has been tried but is not recommended. The value of t_c cannot be determined with sufficient accuracy by direct inspection from the f-curve. A large personal equation may be involved in its determination, and values of K_f derived in this way by two independent workers may easily differ so much as to give widely different f-curves.

The value of K_f so determined can be checked by computing the corresponding f-curve and comparing it with the original, but to secure agreement therewith may require the use of two or three trial values of f_c, and so the labor of determining K_f becomes even greater than where the method of intersections or the logarithmic method is used.

The following method of deriving K_f from an f-curve is much simpler than any of the three methods described, and gives results of a high order of accuracy.

The total or mass-infiltration, in inches depth, from the beginning of rain (t = 0) to the time t is

$$F = \int_0^t f \, dt \quad (4)$$

Substituting the value of f from (1) and integrating gives

$$F = f_c t + [(f_0 - f_c)/K_f] [1 - e^{-K_f t}] \quad (5)$$

The second term in the right-hand member of (5) represents the total mass-infiltration in time t taking place at rates in excess of f_c or, referring to Figure 2, it represents the area between the f-curve, abc, and the asymptotic line, od, for any time-interval t. Taking t equal to infinity, the

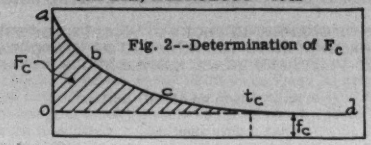

Fig. 2--Determination of F_c

right-hand term of (5) reduces to

$$F_c = [(f_0 - f_c)/K_f] \quad \text{and} \quad K_f = [(f_0 - f_c)/F_c] \tag{6}$$

This quantity F_c does not differ appreciably from the area oabc from $t = 0$ to $t = t_c$, and this area can be determined accurately from the f-curve by averaging the ordinates between zero and t_c or by planimeter-measurement. Hence the value of F_c is known and K_f can be determined at once by substituting this value of F_c in (6). Using the example shown on Figure 1, the value of F_c measured from the curve is 0.506 inch, $f_0 = 2.14$ iph, $f_c = 0.26$ iph, $(f_0 - f_c) = 1.88$ iph. From (6) this gives $K_f = 3.72$ as compared with 3.70 derived by the intersection-method.

In another example, with widely different conditions and from a different series of experiments, F_c derived from the curve = 0.2145, $f_0 = 2.045$, and $f_c = 0.145$. This gives $K_f = 8.88$, which is in good agreement with the value 8.75 derived by the intersection-method.

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[1] ROBERT E. HORTON, Analysis of runoff-plat experiments with varying infiltration-capacity, Trans. Amer. Geophys. Union, 1939, pp. 693-711.
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Voorheesville, New York

DISCUSSION

H. B. INGERSOLL (Soil Conservation Service, Washington, D. C.; communicated)--The paper presents a direct and useful method of determining the value of K_f. The other constants, f_0 and f_c, may be determined as described by the author in his analysis of NEAL'S experiment [author's reference 1].

These constants apply to the infiltration-capacity curve; not to the so-called (i - q)-curve, or to the (i - q')-curve, wherein the (i - q)-curve is corrected for surface-detention. To derive infiltration-capacity curves, estimates must be made for the values of surface-detention, depression-storage, and interception. Then, to calculate surface-runoff from an infiltration-capacity curve, it is necessary to use these values again as they are not reflected in the infiltration-capacity curve.

Where infiltration-capacity curves are being used in surface-runoff evaluation, values of K_f, f_0, and f_c are required to permit a rational means of averaging or compositing several observations. It is sometimes assumed that the composite infiltration-capacity curve, derived from several "runs" under the same conditions, is obtained more readily by compositing the infiltration-constants than by mere averaging of ordinates of various curves for individual "runs". But where surface-runoff is being estimated by "analogy", that is, by assuming that the hydrograph for an average "run" under given conditions is analogous in every respect to that for a typical unit of area, it is sometimes considered unnecessary to derive the infiltration-capacity curve. For this method surface-detention as observed is modified to appear at its relative time of generation, and the resulting curve, rather than the infiltration-capacity curve, is used. Such curves are usually different for different rainfall-intensities, but the infiltration-capacity curve is usually considered relatively constant, hence values of K_f, f_0, and f_c are real reflections of basic constants. On the other hand, these constants cannot be derived without estimating values of depression-storage, interception, and possibly other phenomena which in themselves are volumetric--and therefore depend on rainfall-intensity. For this reason, the ultimate effect of variations in rainfall-intensity must be considered, no matter which type of curve is used, before surface-runoff can be calculated from infiltrometer-experiments.

EXTENSION OF GRAPHIC METHODS OF ANALYSIS OF SPRINKLED-PLOT HYDROGRAPHS TO THE ANALYSIS OF HYDROGRAPHS OF CONTROL-PLOTS AND SMALL HOMOGENEOUS WATERSHEDS

A. L. Sharp and H. N. Holtan

Introduction

The development of the plans of Infiltration Studies (under the direction of G. W. MUSGRAVE, Office of Research, Soil Conservation Service, United States Department of Agriculture, Washington, D. C., and with the cooperation of the Hydrologic Division, same office) to make simultaneous studies of small watersheds by means of infiltrometers and small control-plots, and the watersheds as a whole, has made it desirable, even necessary, to develop more precise methods of analyzing hydrographs of such control-plots and the small watersheds. Following is a proposed method of extending and adapting the graphic method of analyzing sprinkled-plot hydrographs developed by the authors for this purpose [see 3 of "References" at end of paper].

At the outset, it must be conceded that the proposed method will result in close approximations only, of certain functions, such as rate of infiltration. It is felt, however, that these functions can be determined closely enough for practical purposes. It is also granted that certain other functions, such as losses to evaporation, transpiration, canopy-interception, and depression-storage must be neglected, or estimated, generally. In a few exceptional storms some approximate determinations of these quantities may be made.

In order to explain most logically and lucidly this proposed method of analysis of hydrographs, it is necessary to discuss briefly occurrences and sequences of occurrences during the rainstorms of which the hydrographs are a result. The rainstorm itself may be quite varied in character. It may begin with low or high intensities and fall continuously, or intermittently, throughout the storm-period. The storm may end abruptly, or taper off more or less slowly. It may have only one peak (period of high intensity), or several such peaks. The storm may come after a period of dry weather or follow closely other storms. The characteristics of the particular storm under study and preceding storms, their amounts, intensities, duration, and proximity, will determine somewhat the technique to be employed in the analysis.

If it be assumed that no storm preceded the one under study in closer proximity than several hours, the following phenomena may, or do, occur during the storm:

(1) Water is supplied at varying rates and amounts in the form of rainfall.
(2) Vegetation, litter, etc., intercept a part, or all, of the rainfall.
(3) A part of the rainfall evaporates before, or after, reaching the vegetation, litter, or soil.
(4) There may be some loss by transpiration from plants.
(5) All, or part, of the rain reaching the soil may be absorbed as infiltration at varying rates, equal to, or less than the rate of "effective rainfall" (by effective rainfall is meant that portion reaching the soil).
(6) When the effective rate of rainfall exceeds the rate of infiltration, a part of the excess rainfall may collect in depressions and part adhere to the surface of the soil. They are both herein included in the term depression-storage.
(7) After the beginning of rainfall-excess, detention (surface-storage above depression-storage and adhesion), begins to accumulate. Detention is the hydraulic head affording the motivating force for runoff.
(8) Simultaneously with the accumulation of detention, surface-runoff begins.
(9) Water infiltrated into the soil may reappear on the surface or in the streams as runoff.
(10) Surface-runoff from some portions of the area may be absorbed by lower portions of the area before reaching the outlet.
(11) Finally, the excess of supply over losses will appear as surface-runoff at the outlet of the area under study.

To summarize the above, of the some eleven phenomena possibly occurring as outlined, more or less simultaneously, only two can be measured directly, namely, rainfall and net runoff. Two, canopy-interception and depression-storage, can be estimated fairly closely as to amount, but not so closely as to rate of accumulation. Errors of estimates of these two values will affect the total amount of infiltration arrived at by the analysis, but will not affect the accuracy of derived rates of infiltration during any part of the storm, excepting the first part, or those parts immediately following considerable periods during the storm with little or no rainfall. Under most conditions two others, evaporation and transpiration, may be neglected in relatively short storms and small

areas. On plots and watersheds other than those with very pervious subsoil, there is likely to be some seepage of infiltrated water into the channels or outlets during and after storms of long duration or a series of storms sufficient to saturate the soil-profile. The amount of such water on plots and small watersheds, however, is not likely to be large as compared to normal surface-runoff. Probably on most control-plots, chosen for their uniformity of soil, slope, and cover, the loss to infiltration on the lower ends of the plots of runoff coming from the upper end of the plots occurs, but not in any great magnitude, particularly when considerable rainfall occurs. In some natural watersheds, however, this loss may be rather great if the valley-soil has higher infiltration-capacity than that on the slopes. Conversely, it will be small, or none, if the valley-soil has the same, or lower infiltration-capacity, as the soil on the slopes.

On the more homogeneous of plots or watersheds, then, the simultaneous occurrences of various phenomena and the impracticability of measuring directly, more of them, makes the analysis of their hydrographs of necessity mostly approximative. The less homogeneity prevails, the lower will be the applicability of each of the curves of the analysis to each subarea. The method of analysis herein described has not as yet been developed to encompass those hydrographs wherein seepage into channels from the slopes, and losses to channel-banks and valleys of runoff from the slopes, are relatively large. In its present form and stages of development, it will apply only to those plots and watersheds where losses are due to interception, depression-storage, infiltration, and detention, and where runoff is the result of rainfall-excess over these losses.

In the analysis of hydrographs of storms on such areas, rainfall and runoff can be measured directly, interception and depression-storage must be estimated, and detention and infiltration determined. Since neither of these latter can generally be measured directly, one must be determined approximately, in order to isolate the other.

In the method developed by the authors for analyzing hydrographs of sprinkled plots, the recession-period, after cessation of rainfall, is used to determine the amount of detention and its relationship to the rate of runoff. After this relationship is established, detention becomes determinative from the measured rate of runoff, thus leaving infiltration as the only unknown (interception and depression-storage having been estimated or determined by other methods) during the period of rainfall. Infiltration thereby also becomes determinate.

The above method differs from some others that have been advanced [see 2 and 4 of "References" at end of paper] in that it provides for the analysis from the end of artificial rainstorms, when rates of rainfall, runoff, and infiltration, and amounts of depression-storage and detention, are sensibly constant, back to the beginning of the storm where all variables other than rainfall are changing more or less rapidly. By this method, then, the procedure is from known and stable conditions into unknown and varying conditions. It is felt that this is a safer approach than one attempting to segregate the several variables at the start of a storm when they are varying rapidly and proceeding from such a doubtful start through the remainder of the hydrograph.

The principles involved in the above method have been extended and adapted for use in the analysis of hydrographs of natural storms on small homogeneous watersheds and control-plots. Just as in the analysis of sprinkled-plot hydrographs, the aim is to separate detention from infiltration, determine the relationship between detention and runoff, and thus have infiltration as the only unknown during the storm-period (interception and depression-storage being again estimated or determined separately), then working backward from stable parts of the hydrograph into more variable parts.

The following symbols will be used throughout the discussion:

i = Intensity or rate of rainfall, inches/hr
P = Mass or cumulative rainfall, inches
q = Rate of surface-runoff, inches/hr
Q = Mass or cumulative runoff, inches
f = Rate of infiltration, inches/hr
f_c = Final constant rate of infiltration, inches/hr
F = Mass or cumulative infiltration, inches
D_a = Surface-detention, or hydraulic head motivating runoff, inches
V_d = Depression- or pocket-storage, inches
C = Canopy-interception, inches
IA = Initial abstractions: Depression-storage plus canopy-interception, inches
t = Time, hours and minutes
t_o = Time of beginning of rainfall

t_e = Time of end of rainfall
t_r = Time of end of recession-runoff
f_r = Rate of infiltration during recession, inches/hr
F_r = Mass-infiltration during recession, inches
q_r = Rate of runoff during recession, inches/hr
Q_r = Mass-runoff during recession, inches
P_a = Mass-rainfall for any part of storm, inches
Q_α = Mass-runoff for any part of storm, inches
q_{fp} = Final peak-rate of runoff, Class-B storms
F_a = Mass-infiltration for any part of storm, inches
f_a = Average rate of infiltration for any part of storm, inches/hr
a = Factor, unity plus ratio (f_a/q_{fp})

Determination of detention

As indicated above, and as in the analysis of sprinkled-plot hydrographs, the first requirement in this method of analysis of natural hydrographs is to determine amounts of detention, D_a, and the relationship between D_a and the rate of runoff, q. Three types of storms and hydrographs best lend themselves to this determination. They may be described as follows, in the order of their desirability:

Storm-classification: Type-A storms--Rainstorms of this type are:

(1) A rainstorm of sufficiently long duration and sustained rate for the rate of infiltration, f, to have become sensibly constant for the latter part of the storm; the storm to have a period of high intensity after the infiltration-rate, f, has become constant at f_c, the period of high intensity to be preceded and followed by short intervals of sufficiently low intensity of rainfall that the rate of runoff will have approached zero.

(2) A rainstorm characterized by intermittent rainfall, or varying intensity of rainfall, of such nature that runoff will proceed intermittently as well, reaching zero approximately at three or more intervals during the last part of the storm. The intervals between peaks of rainfall when the intensities are low and runoff is approximately zero, however, should be short enough for initial abstraction not to depreciate during periods of low rainfall and runoff. Storms and hydrographs of this type are more easily distinguished than are those under (1) above.

Type-B storms--A rainstorm sufficiently long for f to have become sensibly constant, or at least to have passed the period of greatest curvature, with a late period of high rainfall-intensity ending abruptly.

Type-C storms--All other types of rainstorms producing runoff in appreciable quantities.

Storm-type A lends itself best to this analysis followed by Types B and C in that order. It will probably be found, however, that more storms fall into Type C than in either of the other Types. The method of arriving at the amount of detention, D_a, and its relationship to rate of runoff, q, for each of the above types of storms follows immediately. Later the method of using this information in analyzing the complete hydrograph is developed.

Examples

Type-A storm--There is illustrated in Figure 1 [1] a storm above designated as Type A-1. (All illustrations used in this discussion contain data obtained from control-plots six feet wide by 72.6 feet long.) This illustration is the analyzed hydrograph of the storm under study. Had the valleys in the intensity and rate of runoff-curves been lower, approaching zero, in the storm, this would have been an A-2 storm instead of A-1. Parts of some of the curves in Figure 1 have been transferred to a work-sheet as illustrated in Figure 2. The curves required on this work-sheet are at least the peaks and valleys of the intensity-of-rainfall curve; the rate-of-runoff curve during the period of the storm to be used for determining D_a-values (that part of the storm when the rate of infiltration was approximately constant), and the (P - Q)-curve. Points for plotting the (P - Q)-curve on the work-sheet may best be obtained with dividers, by obtaining differences between the P- and Q-curves on the first sheet at sufficiently close time-intervals, and setting these points on the work-sheet at the proper times. Three curves will now appear on the work-sheet, the i- and q-curves and the plotted (P - Q)-curve. The problem now is to determine the amounts of D_a and the relationship of these values to the rates of runoff.

In order to most clearly understand the problems involved in the determination of D_a, it is necessary that the contents of the (P - Q)-curve be thoroughly understood. This curve is the result

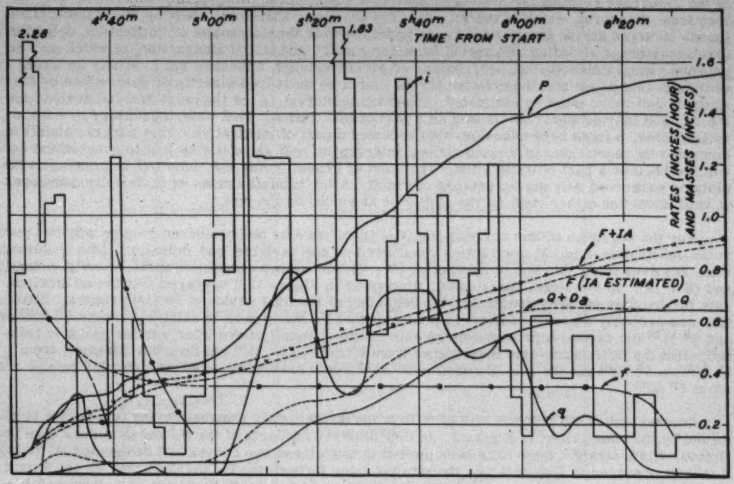


Fig. 1--Type "A" storm, September 7, 1941 (modified), control-plot 6, slope 17 per cent, corn in rotation

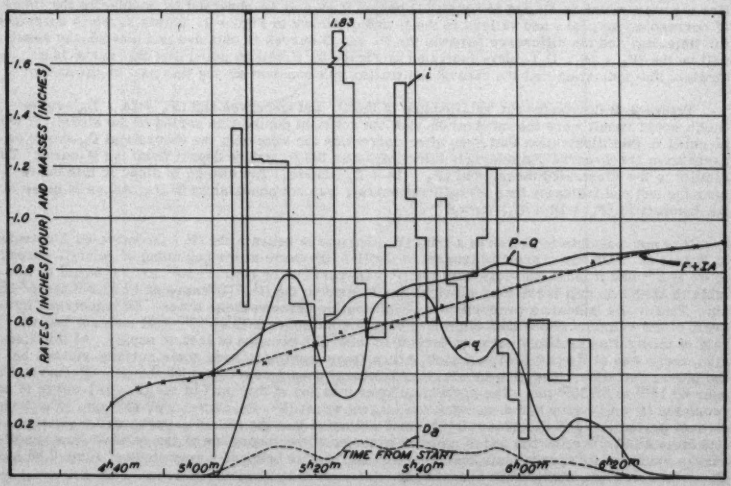


Fig. 2--Work-sheet, Type "A" storm illustrated in Fig. 1

of the difference between the measured source of supply, precipitation, and the only measured loss from the storm, which is runoff. The (P - Q)-curve, therefore, contains all immeasurable losses incurred during the storm. These immeasurable losses consist of infiltration, detention (surface-storage affording motivating force for runoff), and initial abstraction (in which may be grouped canopy-interception, depression- or pocket-storage, adhesion, etc.). It was indicated earlier in this paper that these latter losses cannot be measured directly or determined by the analysis and hence must be estimated. Depression-storage is for the most part infiltrated into the soil and may properly be classed as a part of infiltration. That water necessary to wet the soil-surface, termed here adhesion, also becomes a part of infiltration. That part of rainfall intercepted by vegetation and termed canopy-interception will generally be lost to evaporation and will not become a part of infiltration. That part of rainfall going into detention is present on the plots or watershed only during periods of runoff. After rainfall ceases or materially decreases in rate, detention either runs off the plot or is absorbed by the plot.

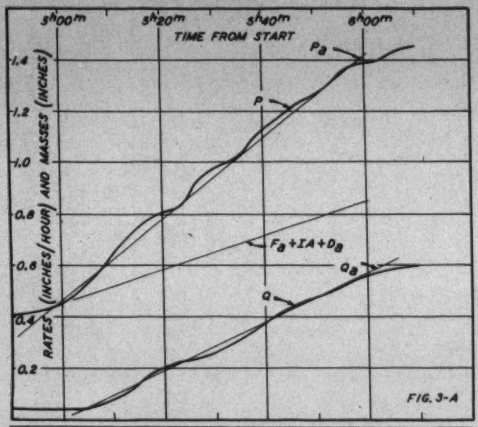
For the purposes of this analysis the (P - Q)-curve may be considered to have only two parts, mass-infiltration + initial abstraction considered as one variable, and detention. The problem, then, resolves itself into one of separating (P - Q) into its two component parts, namely, detention and (F + IA). In the storm under study, illustrated in Figure 1, it appeared that the infiltration-rate had become sensibly constant at the beginning of the final period of rainfall-excess. That this was probably true was indicated by the fact that the early peak in rainfall between $5^h\ 00^m$ and and $5^h\ 15^m$ pm caused approximately as high a rate of runoff as did later similar peaks in rainfall. Had the infiltration-rate been higher from $5^h\ 00^m$ to $5^h\ 15^m$ pm than, for example, from $5^h\ 30^m$ to $5^h\ 40^m$ pm the rate of runoff at $5^h\ 15^m$ would have been lower than was the rate of runoff at $5^h\ 40^m$.

Another indication that the rate of infiltration was sensibly constant during this period is afforded by the comparison in Figure 3. In this illustration, parts of the P- and Q-curves have been plotted. Also, straight lines have been plotted through these two curves and designated P_a and Q_a. It will be observed in Figure 3 that the straight lines through the P- and Q-curves do not depart from the true curves until near the beginning of the period of rainfall-excess at approximately $5^h\ 00^m$. The straight line through the Q-curve departs from the Q-curve slightly later than does the straight line through the P-curve. The difference in the time of departure is approximately five minutes, which is the lag in time of Q behind P as may be observed by comparing the times of corresponding peaks and valleys in the i- and q-curves in Figure 1. If this curve is corrected for time-lag, and the difference between the P- and Q-curves is obtained and plotted, the result will be the $(F_a + IA + D_a)$-curve indicated in Figure 3. It will be noted that this curve is a straight line indicating that the rate of infiltration was constant during this part of the storm.

Figure 3-B illustrates the relationship of the P- and Q-curves and $(F_a + IA + D_a)$-curve which would result were the infiltration-rate not constant during this period of the storm. It will be noted in this illustration that even after correction for time-lag, the theoretical Q_a-curve departs from the Q-curve considerably later than does the P_a-curve depart from the P-curve. This results in the illustrated theoretical $(F_a + IA + D_a)$-curve. The change in slope in this curve near the left end indicates that the infiltration-rate was not constant up to the change in slope of the theoretical $(F_a + IA + D_a)$-curve.

It is now possible to sketch in a trial (F + IA)-curve beneath the (P - Q)-curve as illustrated in Figure 2. This curve must be tangent to the (P - Q)-curve at the beginning of rainfall-excess at $4^h\ 57.5^m$ and it must converge with the (P - Q)-curve at or near $6^h\ 30^m$ pm. It would be possible to sketch in this curve as a straight line tangent to the (P - Q)-curve at $4^h\ 57.5^m$ and $6^h\ 35^m$ pm. This would indicate a constant rate of infiltration between these times. An inspection, however, of the rainfall- and runoff-curves in Figure 1 subsequent to $6^h\ 15^m$ will indicate that the rate of infiltration probably began to decline at this time because of lack of supply. At this time, also, there was still considerable runoff, hence there must have been some surface-storage on the plot at that time. The (F + IA)-curve, therefore, cannot converge with the (P - Q)-curve at or near $6^h\ 15^m$ to $6^h\ 20^m$ pm. The probable proper location of this part of the (F + IA)-curve is between the (P - Q)-curve and a straight line tangent to the (P - Q)-curve at $6^h\ 35^m$ pm. The tests already performed and illustrated in Figure 3 indicated that the (F + IA)-curve was a straight line from $4^h\ 57.5^m$ up to the end of rainfall-excess and the inspection of the rainfall- and runoff-curves indicated its approximate location at $6^h\ 20^m$ pm as being of a magnitude of some 0.85 inch. The trial curve was sketched in accordingly.

The trial (F + IA)-curve, located as above described, divides (P - Q) into two component parts, (F + IA) and detention. The ordinates below this curve represent (F + IA), while the ordinates between the (F + IA)- and (P - Q)-curves represent detention, D_a. Points for a D_a-curve



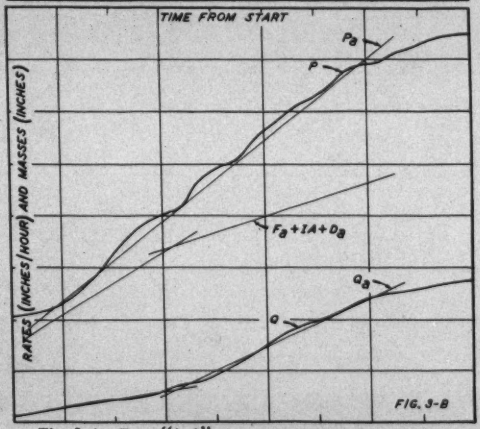


Fig. 3-A--Type "A-1" storm, method of classification illustrated in Fig. 1

Fig. 3-B--Typical illustrative curves indicating storm not in Type "A" class (Type "C" analysis required)

may now be obtained with dividers by obtaining differences between the (P - Q)-curve and the (F + IA)-curve and plotting these points up from the base of the graph. The D_a-curve may then be drawn in to fit these points. There should be, in this curve, peaks and valleys to correspond to the peaks and valleys in the q-curve. These peaks and valleys, however, will precede the peaks and valleys in the q-curve by the amount of time-lag between the i- and q-curves. Pairs of values may now be obtained for D_a and q for plotting a curve of q versus D_a on log log paper. Any given value of D_a obtained from the D_a-curve should be paired with a value of q obtained from the q-curve occurring the time-lag later. The peaks and valleys in the D_a- and the q-curves will afford the most reliable pairs of values of D and q for plotting on log log paper. In order to obtain

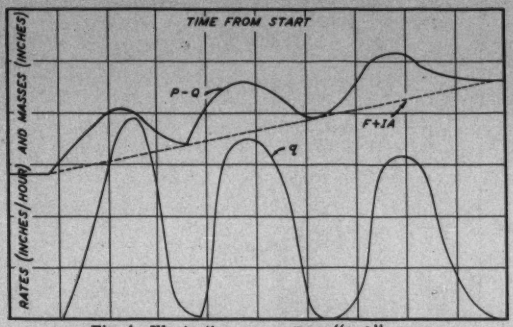


Fig. 4--Illustrative curves Type "A-2" storm

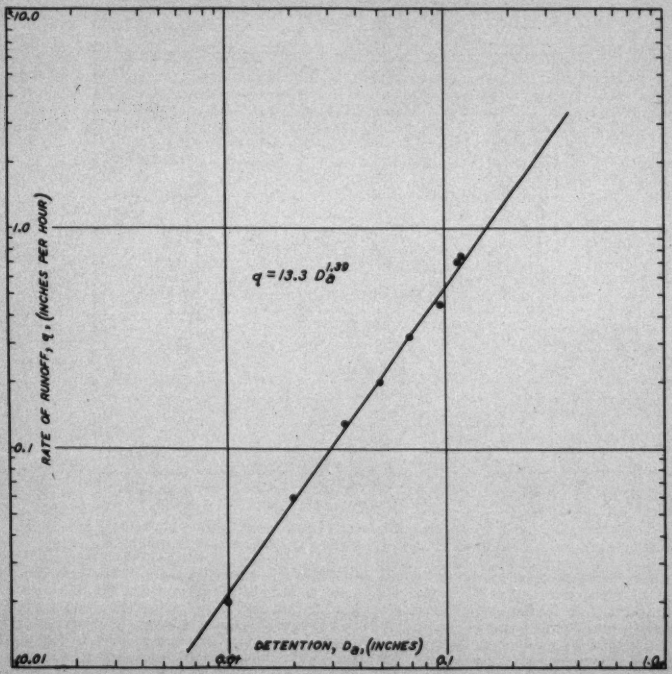


Fig. 5--Detention-runoff graph, Type "A" storm, September 7, 1941 (Figs. 1 and 2)

points of low values of D_a and q for the lower end of the (D_a versus q)-curve, it may be necessary, however, to use the recession-period where values are lower. Pairs of values of q and D_a thus obtained may now be plotted on log log paper with the results illustrated in Figure 5.

The trial (F + IA)-curve sketched in Figure 2 may now be checked by deducting, from (P - Q), values of D_a obtained from the (q versus D_a)-curve on log log paper. The time-lag, however, must again be considered in deducting D_a-values from the (P - Q)-curve. The check-points obtained in this particular instance appear in Figure 2. It will be noted that all of these points do not fall exactly on the (F + IA)-curve. This is due, in part at least, to the variation in time-lag between i and q for various parts of the storm and partially to the possible slight dissimilarity between the shapes of the (D_a versus q)-curves on the rising and receding sides of the hydrograph. They do not vary from the (F + IA)-curve sufficiently, however, to indicate that this curve should be other than a straight line. The analysis of the earlier portion of the hydrograph is now possible. This will be discussed later in this paper.

The analysis of Type A-2 storms is almost exactly like that discussed above for Type A-1 storms, the only difference being that at all times during the storm, when intensity of rainfall is low enough that runoff will practically cease, it will be possible to obtain points on the (F + IA)-curve, thus enabling it to be sketched in through the several points thus established. Because these several points on the (F + IA)-curve are obtainable, it will not be necessary to perform the checks regarding the constancy of rate of infiltration as illustrated in Figure 3. The trial (F + IA)-curve will be tangent to the (P - Q)-curve at the several points where the rate of runoff is practically zero. This is illustrated in Figure 4. After the (F + IA)-curve is sketched in, the procedure is exactly as with storms of Type A-1. Because of its similarity to Type A-1 storms, this type of hydrograph is not included in the illustrations in this paper.

Type-B storm--A different technique may be used in analyzing storms of Type B, although this Type may be analyzed by the methods outlined for Type C, if desired. In Type-B storms, illustrated in Figures 6 and 7, the mass-rainfall curve, P, reaches a maximum and flattens out very rapidly with the abrupt cessation of rainfall. The mass-runoff curve, Q, rises similarly to the mass-rainfall curve but does not flatten out as rapidly after rainfall ceases as does the P-curve because the accumulated detention affords a source of supply for runoff after cessation of rainfall. The method of determining D_a and its relationship to rate of runoff, q, in storms of Type B is very similar to that above referred to for sprinkled-plot hydrographs [3].

Near the time of end of rainfall, t_e, the rate of runoff has become a maximum, D_a is fully supplied, infiltration is continuing, C and V_d have been satisfied and rain is falling. Subsequent to time t_e, rainfall has ceased but runoff and infiltration continue, although at decreasing rates because of exhaustion of supply. From time t_e to time t_r, the end of the recession-runoff period, the only source of supply for runoff and infiltration is D_a in transit (V_d will also furnish a supply for infiltration but is not considered here as it does not enter into the determinations). Intense natural rainfall seldom, however, ceases instantaneously, as is possible with rainfall-simulators, but may decrease rapidly in rate for a short period before cessation. This rainfall, therefore, supplies part of runoff and infiltration during the recession-period. The problem, then, is to deduct the supply from rainfall to recession-runoff and infiltration from that supplied by D_a during the recession-period, and also to correct for losses of D_a to infiltration, in order to determine the amount of D_a and its relationship to q. A method of obtaining these ends is illustrated in Figure 7

In Figure 6 the analyzed hydrograph of a storm of Type B is illustrated. In Figure 7 the final parts of the P-, Q-, and q-curves have been recorded on what might be termed a work-sheet. It will be noted in this illustration that horizontal base-lines have been drawn through the maximum points reached by P and Q. The final portion of the Q-curve and its base are then moved up onto the P-curve so that the bases of the P- and Q-curves coincide. This move may best be accomplished by setting off on dividers distances from the Q-base to the Q-curve then setting this amount down from the base of the P-curve. A series of points thus may be obtained for plotting the new Q-curve from the base through the maximum reached by P. The P and "set up" Q-curve will cross in the earlier part of the storm when D_a is being supplied.

The difference between the "set up" Q-curve and the P-curve, for practical purposes, may be considered as the amount of runoff supplied by detention, D_a. This is based on the assumption that none of the diminishing rainfall-supply is infiltrated directly, all of the rainfall going into detention and that detention only is supplying runoff and infiltration. This assumption is correct for those parts of the plot still covered by detention but erroneous for those portions of the plot where detention has been exhausted. In rainstorms of Type B which decline much more rapidly than D_a is depleted, this direct loss of precipitation to infiltration is so small in amount that it cannot be

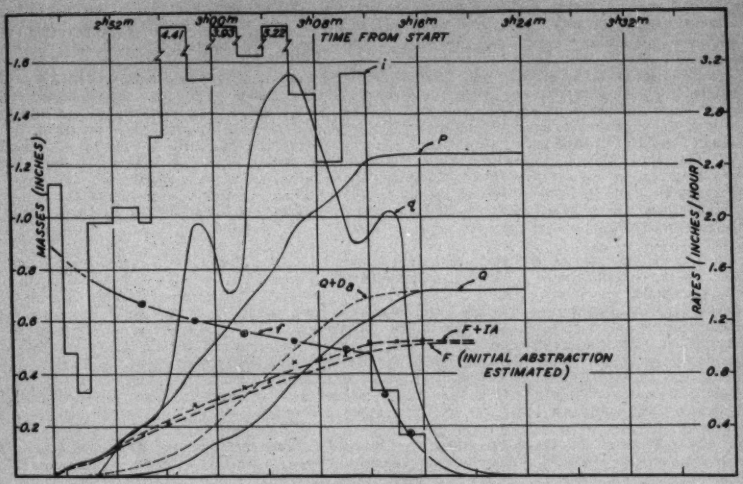


Fig. 6--Type "B" storm, June 7, 1940, control-plot 4, slope 17 per cent, barley and meadow in rotation

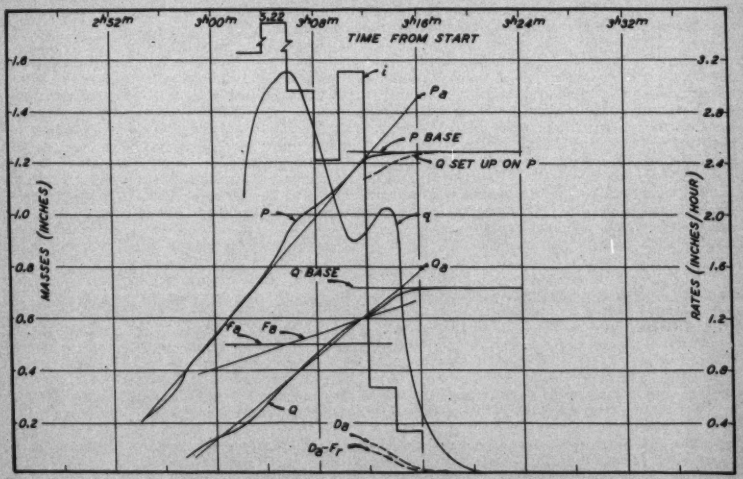


Fig. 7--Work-sheet, Type "B" storm illustrated in Fig. 6

represented on the vertical scales used for such hydrographs. It may, therefore, be neglected without affecting the validity of the results of the analysis. If this loss is measurable the storm is not of Type B.

That the difference between these two curves, P and "set up" Q, is the net supply from D_a to runoff during this period may best be visualized by turning the work-sheet upside down and considering the "set up" Q-curve as a source of supply and the P-curve as a loss, time t_r being considered as zero-time, since in effect, the negative values of these curves are used to obtain the supply from D_a to runoff.

Studies reported in the authors' method of analyzing sprinkled-plot hydrographs indicated that losses to infiltration during recession-periods could be approximately determined and thus permit obtaining D_a-values from recession-periods. In that paper, the assumption was made that the recession-runoff and recession-infiltration curves were similar, had some direct ratio to each other, that

$$D_a = \Sigma q_r(1 + f_e/q_e) \tag{1-a}$$

where Σq_r is accumulative recession-runoff from time t_r back to time t_e, and f_e and q_e are rates of infiltration and runoff, respectively, at time t_e. Σq_r in the above equation is what is termed $(D_a - F_r)$ in this discussion, being the difference between the two measured quantities P and Q. This assumption, later in that paper, was demonstrated to be substantially correct.

Could natural rainfall be terminated as quickly as can that of rainfall-similators, it is logical to expect that the recession-curves of runoff and infiltration of natural storms would have the same similarity as they have in artificial storms, because the occurrences would be exactly similar. Natural rains, however, do not generally end so abruptly, but if the above theory is correct for rainfall ending abruptly, it should be true for that period between times t_e and t_r when there is no rainfall, even though rate of rainfall did not drop from its high intensity to zero instantaneously at time t_e. This relationship between the rate of runoff and infiltration would become less and less correct, however, back from time t_e as rainfall-intensity becomes greater, until i is greater than f, when it would cease altogether to apply.

If the above relationship is true, the $(D_a - F_r)$-curve in Figure 7 may be approximately corrected to obtain a D_a-curve by the methods used in sprinkled-plot hydrographs. The difficulty, however, is in determining the values of f and q to be substituted in equation (1-a). A method of obtaining these values is illustrated in Figure 7. Draw straight-line average curves P_a and Q_a through the P- and Q-curves and obtain the differences in the P_a- and Q_a-curves for plotting an F_a-curve. The slope of the F_a-curve will be f_a. This average f_a-value will pertain, for practical purposes, up to the time i becomes less than f, but thereafter f will begin decreasing because of lack of supply. Some value less than f_a, the value of f_r at t_e, is the proper one to use but there is no method of determining this rate until the hydrograph is analyzed.

The f_a-value thus determined, however, will probably not be much greater than f_e, the rate of infiltration at time of cessation of rainfall, and can be used in a first trial. The final peak-rate of runoff, q_{fp}, near time t_e also may be used as a first trial.

The above equation (1-a) becomes

$$D_a = (D_a - F_r)\,(1 + f_e/q_e)$$

if $(D_a - F_r) = \Sigma q_r$. Substituting in this equation f_a for f_e and q_{fp} for q_e, equation (1-a) becomes

$$D_a = (D_a - F_r)\,(1 + f_a/q_{fp}) \tag{1-b}$$

This may be rewritten

$$D_a = a(D_a - F_r) \tag{1-c}$$

where $a = (1 + f_a/q_{fp})$.

By use of this equation, after substituting the numerical values of f_a and q_{fp}, ordinates of the $(D_a - F_r)$-curve may be corrected to obtain points for a trial D_a-curve. Ordinates of this curve may now be paired with rates of runoff obtained from the q-curve, time lag again being considered, and plotted on log log paper, as illustrated in Figure 8.

Values of D_a should now be obtained from the trial (D_a versus q)-curve and added to the Q-curve, as in Figure 6, to obtain a (Q + D_a)-curve--lag again being considered. Points for a trial (F + IA)-curve then can be obtained by setting off the differences between the P- and (Q + D_a)-curves and plotting these differences up from the base-line of the hydrograph. These points will serve to reveal errors in the ratio of (I_a/q_{D_a}). If the points during periods of high runoff are constantly below a trial average (F + IA)-curve plotted through the above points, the above ratio is too large. On the other hand, consistently high points during periods of high runoff will indicate a ratio too small. This ratio may now be arbitrarily corrected and new curves of D_a versus q, (Q + D_a), and (F + IA) obtained. Thus, by trial and error, the final proper ratio for use in equation (1-c) will be found. It will rarely be necessary to make more than one correction of the a-factor in equation (1-c) after gaining a little experience.

The above relationship between high or low check-points, during periods of high rates of runoff, on the (F + IA)-curve and an erroneous a-factor in equation (1-c) is due to the fact that changes in the magnitude of factor a changes only the position of the (D_a versus q)-curve and not its slope. Shifting this curve right or left changes the magnitude of D_a much more, arithmetically, at high q-values than when q is small.

After the proper (D_a versus q)-curve is obtained, the analysis of the hydrograph may be completed, as will be discussed later.

Type-C storm--There is illustrated in Figure 9 an analyzed storm of Type C. In Figure 10

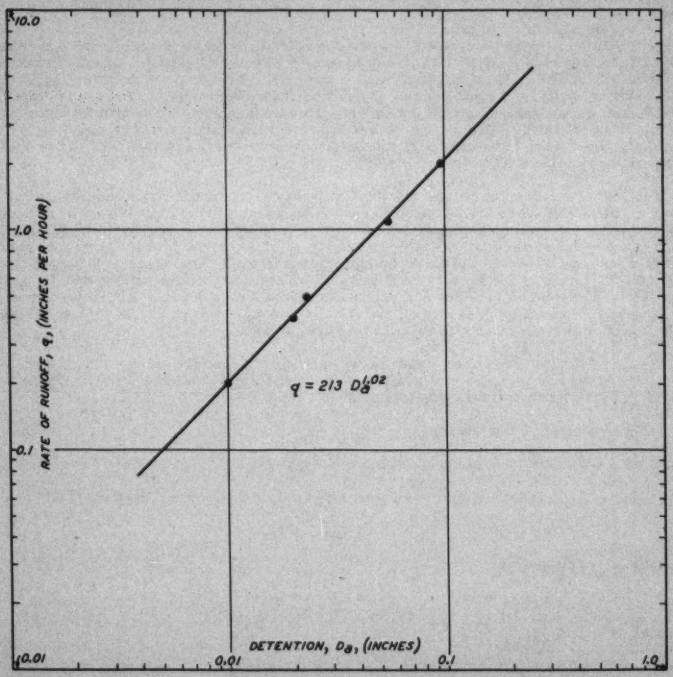


Fig. 8--Detention-runoff graph, Type "B" storm, June 7, 1940 (Figs. 6 and 7)

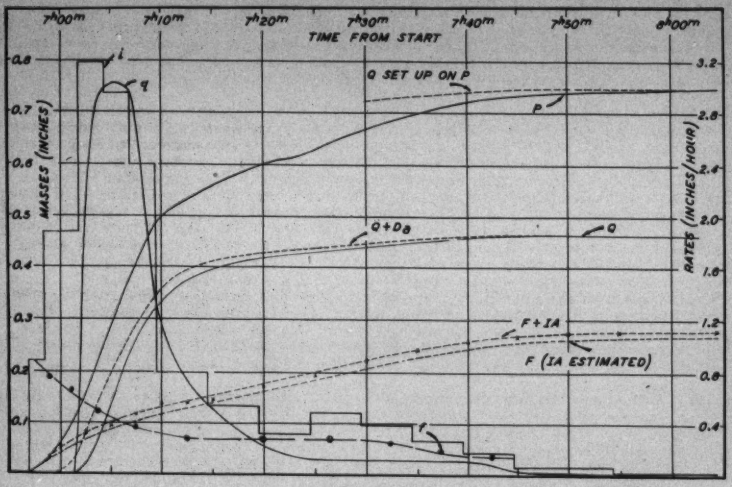


Fig. 9--Type "C" storm, July 8, 1938 (modified), control-plot 3, slope 17 per cent, corn continuous

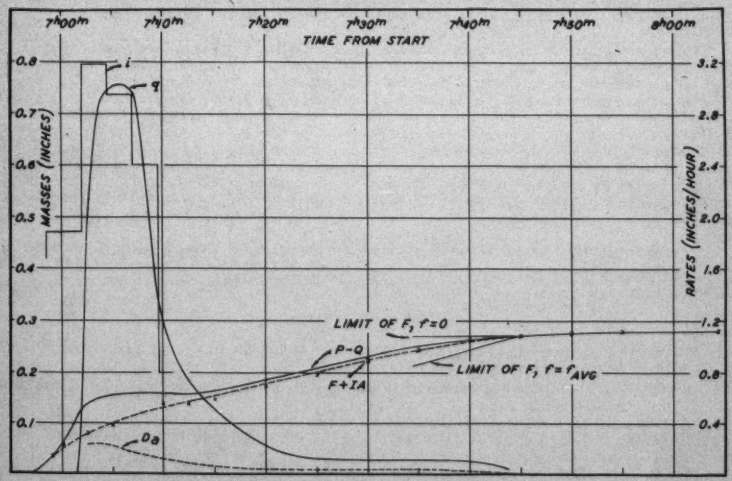


Fig. 10--Work-sheet, Type "C" storm illustrated in Fig. 9

parts of several curves appearing in the hydrograph have been removed to a work-sheet to illustrate the method of determining the relationship between D_a and q. In the analyzed hydrograph, Figure 9, there is one curve not required in the final analysis. This is the Q-curve set up on P. It will be noted that this curve falls above the P-curve indicating that this storm is not of Type B, but falls in Type C, hence a different method of analysis must be used. The need for determining the storm-type is the reason for including this curve.

Figure 10 contains the entire rate of runoff-curve, q. There is also plotted on this Figure enough of the intensity of rainfall-curve, i, to indicate the approximate lag between rainfall and runoff. The next curve to be plotted on this work-sheet is the (P - Q)-curve. This may be accomplished as discussed under Storm-Type A-1. It is now necessary to sketch in under the (P - Q)-curve a trial (F + IA)-curve. This curve will coincide with the (P - Q)-curve when the rate of runoff is, for all practical purposes, zero, as from $7^h\ 45^m$ to $8^h\ 00^m$ pm in Figures 9 and 10. The (F + IA)-curve will depart from the (P - Q)-curve when there is an appreciable amount of runoff as prior to $7^h\ 45^m$. If it is remembered that the slope of the (F + IA)-curve at any given point is the rate of infiltration at that point, the limits of the slope of the (F + IA)-curve can be rather definitely established at this point of departure from the (P - Q)-curve. A horizontal line back of this point would have a zero-slope and thus would indicate a zero-rate of infiltration at this time. A straight line from this point back to zero at the time rainfall began in any appreciable quantities would indicate an average constant rate of infiltration throughout the storm. Probably neither of these rates occurred at this time, the rate being above zero and less than an average constant rate throughout the storm. The proper slope and location of the trial (F + IA)-curve, therefore, lies between these two limits and should be so sketched in as indicated in Figure 10.

A trial D_a-curve may now be obtained. Differences between the (P - Q)-curve and the trial (F + IA)-curve should be obtained with dividers and points plotted up from the base-line for this trial D_a-curve as illustrated in Figure 10. After this trial D_a-curve is obtained, pairs of values of D_a and q should be obtained from their respective curves for plotting on log log paper. Again, however, lag in time between peaks of rainfall and peaks of runoff must be considered. In this particular illustration this lag is approximately 2-1/2 minutes. The D_a-value read at $7^h\ 05^m$ should be paired with the rate of runoff at $7^h\ 07.5^m$, for example. The resulting curve on log log paper should approximate a straight line sloping up to the right. If a straight line does not fit the plotted points fairly well, it is an indication that the trial (F + IA)- and D_a-curves are in error. Another (F + IA)-curve must then be sketched in and another trial D_a-curve obtained.

Values of D_a should now be taken from the curve of D_a and q, these values being deducted from the (P - Q)-curve on the work-sheet. This will result in a series of points as illustrated in Figure 11. These D_a-values must be deducted from the (P - Q)-curve at points preceding the time of reading rates of runoff the amount of lag between the i- and q-curves. If the check-points thus obtained do not fall on or near the trial (F + IA)-curve, it is necessary to sketch in a new trial (F + IA)-curve, and obtain a new curve of q- and D_a-values, thus by trial and error arriving at satisfactory (F + IA)- and (q versus D_a)-curves. Erroneous (q versus D_a)-curves--those with points falling in a straight line but with the wrong slope--will result in impossible (F + IA)-curves. In other words, the resultant (F + IA)-curve may be too steep in its early portion with zero or negative slopes in its latter portion, or increasing steepness from its early portions to its latter portions.

Errors in slopes of the (q versus D_a)-curves of Types A and B storms, particularly Type B, which is more subject to error than Type A, will be reflected by the (F + IA)-curves in this same manner.

Analysis of the hydrograph

The analysis of the whole hydrograph, after a curve of values of D_a and q are obtained, is fairly simple. It may be divided into the following steps:

(1) Plot the i-, P-, q-, and Q-curves on an open time base-scale, and often with P and Q on a scale more open than that of i and q.

(2) Determine the lag between peaks of rainfall and runoff.

(3) Obtain rates of runoff from the q-curve, and corresponding values of D_a, from the (q versus D_a)-curve on log log paper.

(4) Add these values of D_a to the Q-curve, at points preceding the q-values, the amount of lag between peaks of rainfall and runoff, and draw in the curve of (Q + D_a).

(5) Obtain differences between the P- and (Q + D_a)-curves and plot an (F + IA)-curve. This curve, generally, should have a decreasing slope from the time f equals i to time t_f, when infiltration becomes constant, and should be a straight line from t_f to the time-rate of rainfall becomes

less than t_c.

(6) Deduct from the mass-infiltration plus initial abstraction curve an estimated or otherwise determined amount of initial abstraction, and draw in the mass-infiltration F-curve. This curve will be parallel to the (F + IA)-curve from near the end of rainfall-excess back to near the beginning of rainfall-excess. From this earlier point back to the time of beginning of rainfall, t_o, these two curves will converge and coincide at t_o.

(7) Determine points on the rate of infiltration-curve, f, by determining the slope of the mass-infiltration curve, F, at intervals and draw in this curve.

(8) Check the f-curve by determining if the area under it equals F at t_e.

Stated thus, the analysis of the hydrograph appears simple. The actual process, however, requires the exercise of some judgment. This is due to the fact, particularly, that the time-lag is not constant throughout the period of rainfall-excess. Generally speaking, lag will be less with higher rates of rainfall and runoff, longer at lower rates. This fluctuation in the time-lag is well illustrated in Figure 6. An inspection of the i- and q-curves in this hydrograph will reveal that differences in time of peaks and valleys of the two curves vary from only slightly over one minute at $3^h\ 06^m$ to almost three minutes at $3^h\ 12^m$. This variation in lag permits the plotting of an approximate curve of $(Q + D_a)$, only. This will result in erratic points for the (F + IA)-curve, some being above, some on, and some below a smooth curve, as doubtless the (F + IA)-curve should be. Quantitatively, the points should not be off a smooth curve more than 0.02 or 0.03 inch, which is sufficiently close for practical purposes. After these points are obtained, a smooth curve can be fitted to them by eye, and yet be within practical limits of accuracy.

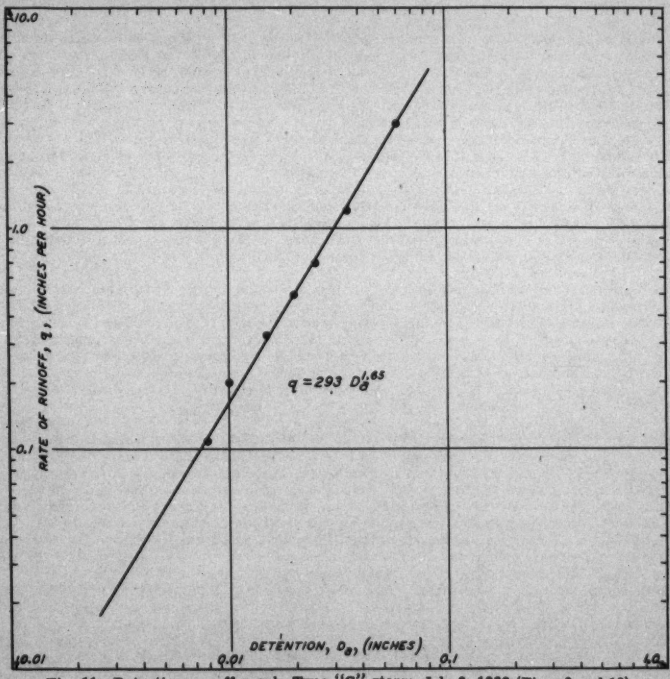


Fig. 11--Detention-runoff graph, Type "C" storm, July 8, 1938 (Figs. 9 and 10)

Illustrations of the complete analysis of the three types of hydrographs discussed appear in Figures 1, 6, and 9. It is felt that these examples are sufficiently illustrative to require no further discussion of the method of completing the analysis, except to point out probable maximum errors in the rate of infiltration-curves.

It will be noted in each of the three hydrographs illustrated in Figures 1, 6, and 9, that estimates have been made of initial abstraction in the amounts indicated by the difference between the F- and (F + IA)-curves. Since initial abstraction is satisfied in the early parts of the storms, errors of estimate of this quantity would affect the position of the F-curve rather than its slope, and hence will not be an error in the position of the infiltration-rate curve. In Figure 1 initial abstraction has been estimated as 0.03 of an inch. This deducted from the (F + IA)-curve results in the illustrated F-curve. It will be observed that this curve could scarcely be lowered more than an additional few hundredths of an inch and still possess the typical shape of mass-infiltration curves. The maximum that it could be lowered and still retain this shape is some 0.05 inch.

In Figure 6 if the estimated value of initial abstraction were increased as much as 0.03 inch, the result would be a practically constant rate of infiltration throughout the storm which is not logical. It would appear, therefore, that the amount of initial abstraction as estimated is of necessity within 0.01 or 0.02 inch of the absolute value. In Figure 9 the same limits of variation of the estimated initial abstraction would probably apply, since lowering the F-curve, which would result from increasing the estimated initial abstraction would again tend to reflect a constant rate of infiltration throughout the storm. As indicated earlier, any errors of estimate of initial abstraction affect the position of the F-curve but do not affect materially the slope of this curve (which reflects rates of infiltration).

The most important likely error, then, in the F-curve is in its slope rather than its position. In Figure 1 it will be noted that the position of the late end of the (F + IA)-curve could not possibly be in error more than 0.02 inch or so, because it must converge with the (P - Q)-curve (illustrated in Figure 2) at some point between $6^h\ 25^m$ and $6^h\ 30^m$ pm. This is because D_a is still on the plot in appreciable quantities up to $6^h\ 25^m$ pm. This (F + IA)-curve cannot be lowered at its earlier junction with the (P - Q)-curve at $4^h\ 57.5^m$ because it must be tangent to the (P - Q)-curve at this time, since there is no detention on the plot immediately preceding this time. If it were too low at this point (should have some curvature following $4^h\ 57.5^m$), a straight-line relationship would not exist between rate of runoff and detention as illustrated in Figure 5. In this particular instance, therefore, the slope of the (F + IA)- and F-curves cannot be in error more than a maximum of some 0.02 or 0.03 inch from $4^h\ 57.5^m$ to $6^h\ 30^m$ pm. An error of 0.03 inch in the F-curve in this time--1 hour and 32.5 minutes--would cause an error of 0.02 inch per hour, approximately, in the magnitude of f_c. If f_c has a value of 0.34 inch per hour, an error of 0.02 inch per hour would be the equivalent of plus or minus some six per cent.

In Figure 6 it will be observed that the position of the F-curve at $2^h\ 52^m$ pm could not be changed materially without resulting in an illogical shape near this time. Likewise, the position of the F-curve at about $3^h\ 12^m$ pm cannot be changed more than 0.01 or 0.02 and be compatible with the proper shape of this curve. The error in increment of the F-curve between $2^h\ 52^m$ and $3^h\ 12^m$, therefore, cannot possibly be more than a very few hundredths inch, say 0.03 at the outside. This maximum error of 0.03 inch in 20 minutes would be equivalent to an error of 0.09 inch per hour in rate, or an error of rate at $3^h\ 08^m$ pm of approximately nine per cent.

In Figure 9 the slope of the F-curve is rather definitely located by the differences in average rates of rainfall and runoff from $7^h\ 15^m$ or $7^h\ 20^m$ to $7^h\ 30^m$ to $7^h\ 35^m$. It will be observed further that the position of the F-curve could not be altered materially in the early part of the storm and have the logical shape of such curves. Furthermore, the position during the latter part of the storm is definitely limited by the position of the (P - Q)-curve illustrated in Figure 10. The (F + IA)-curve cannot converge with the (P - Q)-curve in this illustration prior to $7^h\ 45^m$ pm because of detention on the plot up to this time, nor can it depart much further from the (P - Q)-curve than illustrated and result in a proper (q versus D_a)-curve, illustrated in Figure 11. It appears, therefore, that the maximum possible error in increment in the F-curve from about $7^h\ 10^m$ to approximately $7^h\ 35^m$ is 0.02 or 0.03 inch, which would be equivalent to an error of not over 0.05 inch per hour in the rate of infiltration. This would result in a larger possible percentage-error than in either the Type-A or Type-B storms. This likelihood of greater error in the analysis of Type-C storms than in Type A or Type B was pointed out earlier in this paper.

Determination of depression-storage

After a hydrograph is thus analyzed, and if a second rainstorm occurs a few minutes there-

after, sufficient time having elapsed for V_d to have infiltrated but not for f to have had time to recover much above f_c, or C to evaporate, the second hydrograph may be analyzed to determine approximately the value of V_d. In such instances

$$V_d = P' - Q' - F' \tag{2}$$

where P' is rainfall, Q' is runoff, and F' is infiltration during the second rainstorm, and

$$F' = f_c(t'_e - t'_o) \tag{3}$$

where t'_e and t'_o are the end and beginning, respectively, of the second storm and i is greater than f_c. If the early portion only of the second storm-hydrograph is used to determine V_d, then D_a, obtained from the (D_a versus q)-curve, must also be deducted from rainfall and the above equation (2) becomes

$$V_d = P' - Q' - F' - D_a \tag{4}$$

This method of determination of V_d serves to check estimations made earlier, and in estimates of V_d-values for other similar plots or areas and storms.

Checks on estimation of canopy-interception, C, may be obtained under some few conditions where there have been sufficient determinations of other variables so they may be eliminated from certain storms. A particularly fortunate set of hydrographs would be necessary for this, however, and such estimates must, generally, be based on other studies designed specifically for measuring directly this quantity.

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QUALITY OF STORED WATER AVAILABLE FOR USE IN THE LOWER BASIN OF THE PECOS RIVER, TEXAS

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(Published with the approval of the Director, Geological Survey, United States Department of the Interior)

Storage of water in reservoirs may be for (1) irrigation, (2) power-generation sometimes in connection with releases for irrigation, (3) flood-control, (4) recreation, or combinations of these four uses. The control of releases of the stored water may involve conflicts of interests as to the best use of the available supply.

Conflicting interests of irrigation and power came to light during the past four years in the use of water stored in the Red Bluff Reservoir on the Pecos River near Orla, Texas (see Fig. 1). In planning for the financing of the construction of the Red Bluff Dam it was estimated that funds from the sale of power developed at the dam would provide about 60 per cent of the annual charges, including costs of operation and maintenance. The "Master Contract" between the Red Bluff District and the seven component districts states: "The property rights and also the burdens and charges incident to ownership, maintenance, and operation of the reservoir and properties, owned, maintained, and operated by the Red Bluff District shall be based upon the value and use of the water for irrigation." The most beneficial operation of this project should obviously be based on consideration of the volume of water available, the probable needs for this water for irrigation and suitability of the stored water for irrigation.

Red Bluff Dam was completed in 1936 and as a result of floods in the spring of 1937 the reservoir was filled to its capacity of 307,000 acre-feet. Water was spilled from the reservoir in June 1937. During the next two years, however, runoff in the upper river was less than average and the

Table 1--Runoff and dissolved solids at the Red Bluff and Orla gaging-stations during the four years ending September 30, 1941

Date	Runoff, acre-feet		Dissolved solids, tons	
	Red Bluff	Orla	Red Bluff	Orla
Oct. 1, 1937-Sep. 30, 1938	131,600	217,600	832,000	1,115,000
Oct. 1, 1938-Sep. 30, 1939	107,400	185,600	736,000	1,197,000
Oct. 1, 1939-Sep. 30, 1940	98,340	110,200	687,000	840,000
Oct. 1, 1940-Sep. 30, 1941	1,198,000	929,500	3,280,000	2,493,000

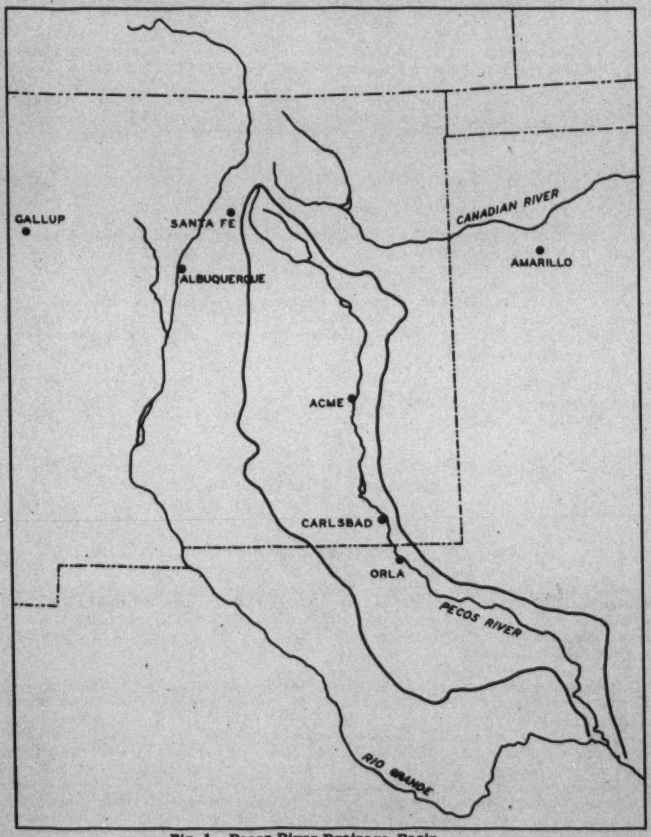

Fig. 1--Pecos River Drainage-Basin

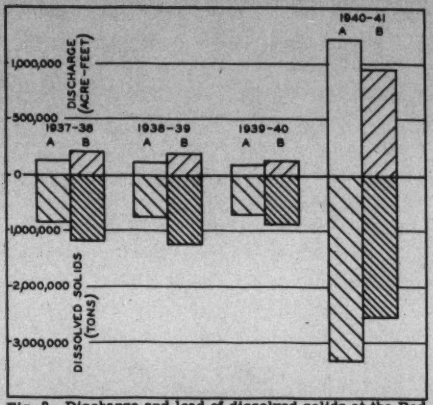

Fig. 2--Discharge and load of dissolved solids at the Red Bluff (A) and Orla (B) gaging-stations on the Pecos River

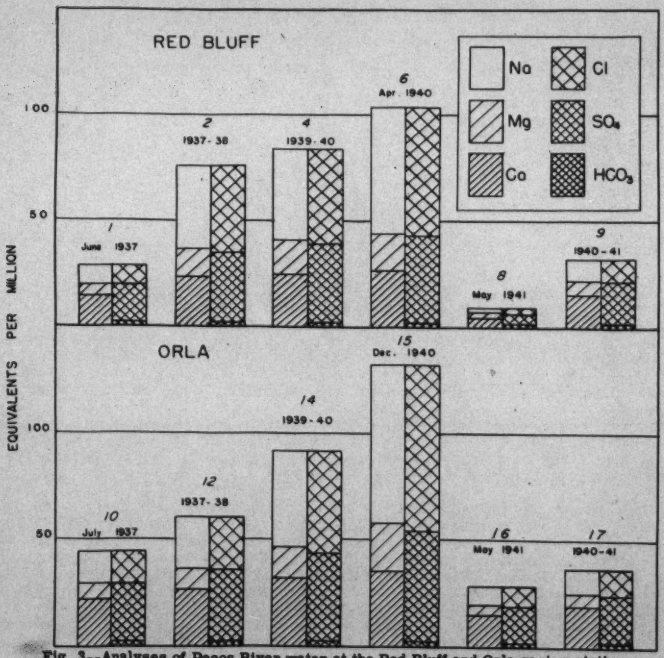

Fig. 3--Analyses of Pecos River water at the Red Bluff and Orla gaging-stations (Numbers above diagrams refer to analyses in Table 2)

Table 2--Analyses of water from the Pecos River at gaging-stations near Red Bluff, New Mexico, and Orla, Texas

(Analyzed by United States Geological Survey)

No.	Date of collection	Mean discharge, second-feet	Specific conductance ($K \times 10^5$ at 25°C	Parts per million						Dissolved solids	
				Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)	Bicarbonate (HCO_3)	Sulphate (SO_4)	Chloride (Cl)	Parts per million	Tons per acre-foot
			Pecos River near Red Bluff, New Mexico								
1	Flood-water of 1937	....	946	288	63	192	90	864	298	1,751	2.38
2	Weighted average, 1937-38	182	668	457	160	928	138	1,572	1,447	4,650	6.32
3	Weighted average, 1938-39	148	714	509	186	964	134	1,775	1,514	5,030	6.84
4	Weighted average, 1939-40	135	734	496	190	1,004	131	1,768	1,578	5,120	6.96
5	March 26, 1941	638	260	308	71	201	113	908	310	1,868	2.54
6	April 11-20, 1941	80.7	916	530	213	1,388	130	1,949	2,160	6,320	8.60
7	May 5, 1941	9,210	219	196	52	233	87	691	288	1,516	2.06
8	May 23, 1941	27,700	87.2	90	19	65	83	225	89	541	.74
9	Weighted average, 1940-41	1,655	270	297	68	267	103	911	397	2,009	2.73
			Pecos River near Orla, Texas								
10	July 1-10, 1937	244	379	442	78	362	88	1,342	525	2,810	3.82
11	July 11-20, 1937	586	514	476	100	613	116	1,472	920	3,650	4.96
12	Weighted average, 1937-38	3,060	508	520	116	573	110	1,614	868	3,760	5.11
13	Weighted average, 1938-39	3,280	646	583	161	794	109	1,892	1,237	4,740	6.45
14	Weighted average, 1939-40	152	786	592	200	1,066	121	2,019	1,668	5,640	7.67
15	December 11-20, 1940	2.7	1,104	702	274	1,715	133	2,464	2,730	7,960	10.8
16	May 26-31, 1941	1,058	252	303	54	203	87	849	318	1,779	2.42
17	Weighted average, 1940-41	1,284	315	364	72	291	121	1,068	434	2,308	3.14
18	September 11-20, 1941	731	434	444	97	471	153	1,342	720	3,180	4.32

releases of water from the reservoir (to some extent for power-purposes) exceeded the inflow. The volumes of water flowing into and out of the reservoir for each of four years are given in Table 1 and shown graphically by the upper diagrams in Figure 2. The volume measured at the Red Bluff gaging-station above the reservoir represents practically the entire volume of inflow. The volume measured at the Orla gaging-station, 19 miles below Red Bluff Dam, consists almost entirely of water released from the reservoir. On a few occasions the Orla record includes some runoff from a small area below the dam. During each of the years 1937-38, 1938-39, and 1939-40 the outflow exceeded the inflow. As a result there was a material lowering of the water in the reservoir but in January 1940, at the beginning of trustee management, steps were taken to regulate release from the reservoir to conserve the water for irrigation. These steps were largely responsible for the smaller excess of outflow over inflow noted for the year 1939-40. The loads of dissolved solids at the Red Bluff and Orla gaging-stations during each of the four years are given in Table 1 and are shown graphically by the lower diagrams in Figure 2.

After completion of the Red Bluff Reservoir in 1936 about 40,000 acre-feet of water, representing low flow of the river, was stored in the reservoir. To this storage over 260,000 acre-feet of flood-waters were added in the spring of 1937. The concentration and character of the water flowing into the Red Bluff Reservoir under different conditions of discharge are shown by analyses 1-9 in Table 2 and Figure 3. The waters of the flood of 1937 are represented by analysis No. 1. The average concentration and composition in years when there was no major flood are represented by the weighted average for the water-year 1939-40 (analysis No. 4). The most concentrated water that would be expected for any extended period at Red Bluff is represented by analysis No. 6. Flood-waters during the water-year 1940-41 are represented by analyses Nos. 5, 7, and 8. Because of the large volumes of water of such low concentration the weighted average for 1940-41, represented by analysis No. 9, is much lower in concentration than the weighted averages for the three

years, 1937-38, 1938-39, and 1939-40 (analyses Nos. 2 to 4). Under normal conditions of storage the inflow of low concentration will not immediately mix with the stored water and when spill occurs some of the less concentrated water will be carried on the reservoir-surface and discharged with only a moderate change in concentration. During storage the overlying water mixes to some extent with the water at greater depths tending to make the stored water uniform in concentration. Except for releases over the spillway all water released from the Red Bluff Reservoir is released at the bottom of the reservoir.

Analyses for the Orla gaging-station representing the water released from the Red Bluff Reservoir are available for a four-year period beginning July 1, 1937. Analysis No. 10 for the period July 1-10, 1937, represents the water released from the reservoir during the period immediately following the flood of 1937. From that date to the last of December, 1940, analyses of the water at Orla showed a progressive increase in concentration. This increase is indicated by the weighted averages for the water-years 1937-38, 1938-39, and 1939-40 given in Table 2 and shown diagrammatically in Figure 3. The analysis of a composite of daily samples collected between December 11 and 20, 1940, (analysis No. 15) showed the highest concentration of the composite of samples collected at Orla during the four-year study. Analysis No. 16 represents samples collected at Orla during one of the floods of 1941. The effect of the low concentration of these waters is apparent by comparison of the weighted averages for the first three years (analyses Nos. 12, 13, and 14), with the weighted average for 1940-41 (No. 17). During several periods in the summer of 1941 the outflow from the reservoir had a concentration of dissolved solids less than 2,000 parts per million but the concentration of the outflow during the period September 11-20, 1941, was 3,180 parts per million (analysis No. 18).

During the water-year 1940-41 the flow into Red Bluff Reservoir was sufficient to have completely filled the reservoir three times. In the report of the Pecos River Joint Investigation an operation study is reported which states that, under certain operation practices for the Carlsbad Project and the Red Bluff District, "It is found that in the 35-year period, 1905-1939, Red Bluff Reservoir would have spilled in six years only, and that the total spill in these years, most of it in two years only, would have been 642,000 acre-feet" [p. 316 of mimeographed report of National Resources Planning Board on Pecos River Joint Investigation in the Pecos River Basin in New Mexico and Texas, 1941]. In the water-year 1940-41 over 600,000 acre-feet of water were spilled from the Red Bluff Reservoir, a volume nearly equal to that estimated for the entire volume of spill in a 35-year period.

The concentration of dissolved solids in the water of the lower Pecos River is usually higher than is desirable for irrigation. The concentration increased from 1937 to 1940 and decreased in the spring of 1941 due to large floods. At the end of the water-year 1940-41 the Red Bluff Reservoir was full of water having a concentration about the same as the concentration of the stored water in July, 1937. Operation of the reservoir for power-purposes has not been allowed since January, 1940, in order to conserve the supply available for the irrigation because the prospects of getting the reservoir filled again soon may be rather small. Inflow into the reservoir during periods of average or low flow will be more concentrated than the water stored in the reservoir at the beginning of the irrigation-season of 1942.

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DISCUSSION

C. S. SCOFIELD (Bureau of Plant Industry, U. S. Department of Agriculture)--Mr. HOWARD has summarized the facts as to the composition and concentration of the salts in the water stored in Red Bluff Reservoir and thus available for use in developing electrical energy and in irrigating lands in the Pecos Valley below the reservoir.

It should be noted that, while the concentrations reported for released water range between wide limits, the values representing the annual weighted averages are all high. Stated in tons per acre-foot, they are: 1938, 5.11; 1939, 6.45; 1940, 7.67; 1941, 3.14.

By way of comparison it may be said that in general, throughout the West, irrigation-farmers try to avoid using water containing more than two tons per acre-foot of dissolved solids. Thus it is obvious that in the interest of irrigation the aim should be to release the best water during the early summer, April to August, and to release any surplus of the saltier water through the power-plant during the other months of the year. This is easier to say than to do, because of the uncer-

tainty as to input. If the seasonal inflow were dependable, the reservoir could be drawn down to remove the residual salts and make room for the better-quality flood-waters. But with the likelihood of many dry months ahead the temptation is strong to hold a reserve, even if it is salty. Then, if a flood of good water does come in, it flows over the reservoir, over the spillway, and is lost. Supplemental reservoir-capacity either above or below Red Bluff is manifestly needed.

I think the agricultural situation in the irrigated lands below Red Bluff could be improved by better coordination of the distribution-systems and by improvement of the canals to diminish percolation-losses which are now excessive. Local experience has shown that it is possible to produce good yields of such salt-tolerant crops as cotton, grain-sorghum, and alfalfa if the land is copiously irrigated even though the water may contain as much as seven to eight tons of salts per acre-foot. But to use such water sparingly is disastrous. The root-zone reservoir must be leached frequently to avoid excessive salt concentration in the soil-solution.

Local experience has shown also that with this salty irrigation-water, good crop-yields are obtained only from the more permeable soils that have ample subsoil drainage. No useful purpose is served by allocating such salty water to soil from which the chief escape is by evaporation. The agricultural situation in the Pecos Valley below Red Bluff could be greatly improved, even with its present water-supply, by readjustments in two directions: (1) By coordinating and improving the distribution-system so as to get more of the water to the land; (2) by allocating the available water to the more permeable and better-drained soils.

ANALYSIS OF NATURAL FLUCTUATIONS IN GROUND-WATER ELEVATION

Carroll F. Merriam

That an ever greater number of ground-water observations are now being taken is attested by the increasing size of the Water-Supply Papers annually devoted to this part of the work of the United States Geological Survey. However, throughout the northeastern part of the country practically all of these data refer to the fluctuations in the water-table in districts where critical conditions have been brought about by excessive pumping. The purpose is primarily to study the artificial rather than the natural fluctuations of the water-table. One important exception is the State of Pennsylvania where weekly observations have been taken at between 25 and 30 wells throughout the State during the past decade.

The measurement of the natural rise and fall is important for two reasons. In the first place these fluctuations are imposed also upon the artificial fluctuations, and consequently any study intending to show the true trend in these latter cannot be complete without some means of taking the former into account, or waiting until considerable time has elapsed. The second reason is that ground-water is an important element in the hydrologic cycle, and thus no analysis of the disposition of precipitation can be comprehensive until the ground-storage is recorded and interpreted.

One phase of this general problem which has already aroused some interest is the connection between ground-water and stream-flow. On account of the excellent opportunity to gauge the flow of the Susquehanna River not far from its mouth, it would seem that here would be an unusual opportunity to collect data which might eventually be of value in exploring further any such relation. Consequently, the area drained by this river was given special study in the hope of developing an index-figure which would express the average rise and fall of the water-table for the basin as a whole. The methods used in this study are believed, however, to be of general application in studying the natural fluctuations of ground-water over large areas.

Where wells are located close to each other, as in districts intensively studied, there is a fairly free hydrostatic connection between them. Consequently, the general rise and fall is in unison, and as demonstrated by LEGGETTE [W.-S. Paper No. 886, p. 479] the average elevation of a few wells does not differ greatly from that of a great number. In this case ordinary arithmetic averaging of the observations gives satisfactory results.

A large area, however, presents an entirely different situation. There seems to be no widespread hydrostatic connection to cause the variations to keep in step, and furthermore there are many dangers that some wells will strike peculiar conditions such as perched water-tables, and other purely local phenomena which may render the reports from them practically useless for the purpose of deriving a representative average, or index. To guard against such misleading results special care must be taken.

Recognizing from the start that observations at wells distributed in a far-flung manner over an area of some 27,000 square miles would be at best merely arbitrary indications, the first attempt to coordinate their readings was to assume that the elevation on a certain date, which happened to be practically at the end of the drought of 1931, should be considered to be 10.0. In this way the datum-planes were established and for several years the elevations referred to them were simply averaged in the usual way. Ten was selected as the common elevation on this date to avoid minus readings, but it has since proved that wells have so seldom been lower that the average is always between 10 and 20, and so the initial digit may now be omitted.

The first step in deriving a common index-value is to disregard, at least tentatively, the wells that do not conform with the rest, that is to say, those that do not rise and fall along with the others. When several years of record were plotted it was easy to pick out by inspection those which showed peculiarities of their own. This first elimination is not at all critical except that if the bad ones can be weeded out initially the work to follow gets a better start. On the other hand, there is no permanent damage if worthy wells are thrown out and unworthy ones left in, for as will be seen later a second check will atone for any unwise selections in this respect.

Once having selected the wells to be used for the first trial, the readings should be averaged in the usual way to give what might be termed the first trial index. The next step is to plot individually the weekly readings of each well against the corresponding first trial average. In so doing all wells, even those tentatively eliminated should be included as it gives them, as it were, another chance to make good.

From this point on the steps might be visualized as a sort of refining process whereby through successive stages the data are first plotted against an arithmetic or first trial average to determine at least roughly the relation that each record bears to this average. Then by means of this relationship the individual readings are in turn translated to the average that would be expected if only one well in question should have been observed. Inasmuch as these expected index-figures are in comparable terms they can likewise be averaged to get a new composite, which would be expected to bring us more closely to the ultimate goal. The process may then be repeated, plotting again the original data against the second set of averages, and since this second index is closer to the ultimate, some of the scatter would be removed from the plotted points. In this way the second determination of the relationship would be more definite than the first. This process could go on ad infinitum but, of course, there is a practical limit when further trials fail to show sufficient improvement to warrant the effort.

In the Susquehanna study the first plottings did not yield very positive results, in fact hardly more than gunshot diagrams. The best that could be done was to draw a straight line which indicated roughly the relation between the individual wells and the first index. It was noted that some of these lines were steep and some flat, thus showing first of all that there was a wide variation in the extent of the fluctuations, some having a normal range of as much as ten feet or more and others hardly a third of this amount.

The marked differences thus seen in the normal ranges of the various wells give rise to difficulties in taking arithmetic averages of the readings in the ordinary way. Obviously the influence of very active wells is disproportionately great, while sluggish wells have a deadening influence. This would not be so objectionable if we could have assurance that observations of the present wells would always be continued, and that no new wells would be added, but that is far from the actual situation. Missing readings are likewise very disturbing, as either they have to be interpolated or else their omission throws out the whole scheme of averaging.

To illustrate the nature of these plottings, two contrasting examples are given in Figures 1 and 2, the first being a very bad well, and the second, one which is very desirable from several points of view. It will be noted that in the case of Well 104 the points scatter entirely at random, whereas Well 106 shows distinct relationship to the general average. Even in this case there is still considerable scatter in the points in spite of several stages of refinement already made. This scatter arises primarily from the fact that ground-water conditions can be expected to vary widely over so large an area and for this reason it is desirable to include as many wells in the average as possible. In spite of the latitude which might be exercised in defining the rating-curve to be used, nevertheless this method of reduction to common terms is effective in protecting against the obvious error of using simply an arithmetic average of the readings regardless of the characteristics of the wells.

After three repetitions of this process of plotting and replotting, all but two wells had begun to show distinct curvature in their ratings, as seen in Figure 3. Some began with a small slope

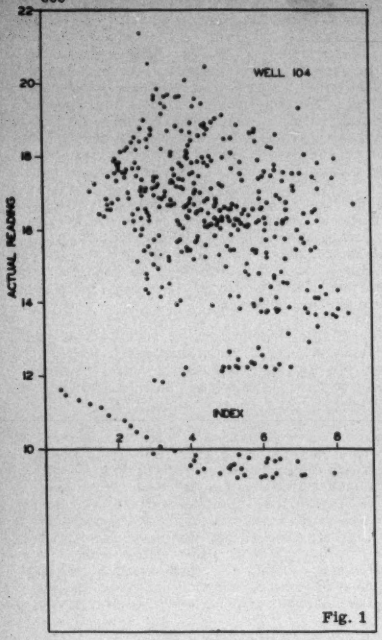

Fig. 1

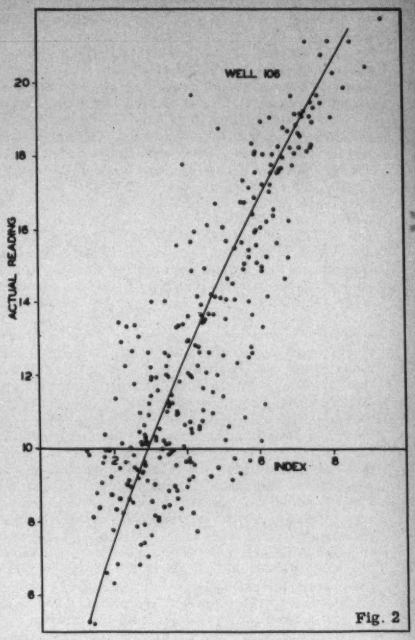

Fig. 2

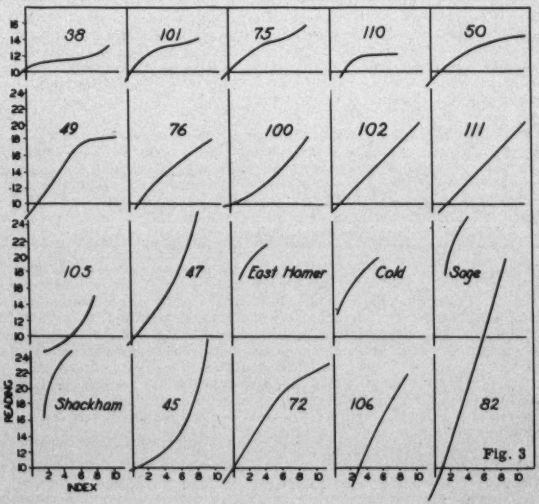

Fig. 3

which increased rather markedly with the higher readings, while others were just the opposite. There were some which reached rather well-defined ceilings, above which the water rose only reluctantly even when the others continued to attain much higher levels. A few had rather definite minimum elevations below which they did not fall.

That there should be a variety of shapes is quite natural when we consider that we are not dealing with an absolute measure, but merely the levels that will be attained by varying amounts of water in soils of decidedly different capacities. The flattening of the tops of the curves may be accounted for in case the wells happen to be too near the spring-line, so that water rising beyond

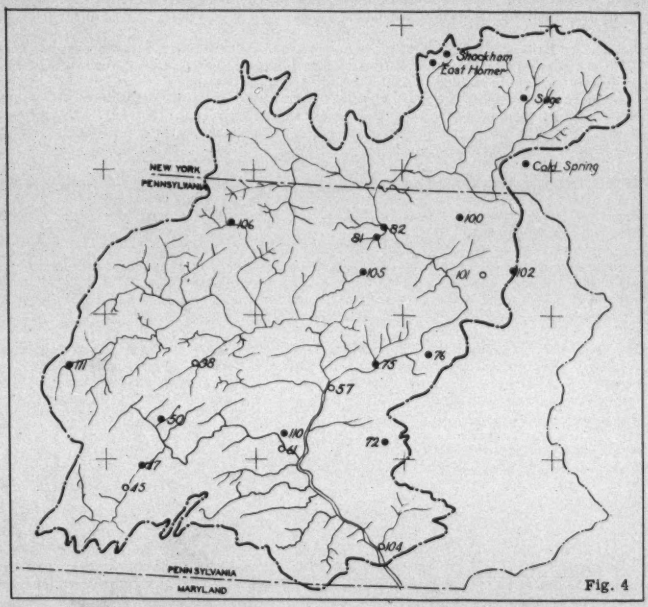

Fig. 4

WELLS USED

No. 47 Fluctuates rapidly. Apparently changed its rating June 29, 1939. Reason unknown.
No. 50 Rating-curve rather flat, but better on lower ranges. Well fluctuates rapidly.
No. 72 Rating-curve has good steep slope. Fluctuates rapidly at higher ranges but is steady at low.
No. 75 Somewhat flashy, but in general the agreement is good.
No. 76 Excellent on high ranges. Rating-curve somewhat doubtful at low.
No. 81 Excellent on higher range. Rating-curve extraordinarily steep.
No. 82 Not good on higher ranges, but excellent on low.
No. 100 Good, with slope increasing for higher ranges.
No. 102 Good.
No. 105 Good on higher ranges, curve flattens at low and well goes dry.
No. 106 Very good and shows excellent agreement with average of the others.
No. 111 Very good.

Cold Spring Not safe when water-surface is within 7.0' of the reference-mark.
East Homer Safe only when the staff-gauge in well reads elevations below 6.0'.
Sage Good only for low ranges when the water-surface is more than 2.0' below reference-mark.
Shockham Not good when water-surface is less than 2.0' below reference-mark. Low range cut short by well going dry.

WELLS NOT USED

No. 38 Unsatisfactory because of flat slope.
No. 45 Very good on higher ranges, but discontinued.
No. 57 Entirely unsatisfactory. Town location in flood plain.
No. 61 Very bad, possibly because of location too close to built up section of town.
No. 101 Disqualified as showing poor relation to others. Slope flat at higher ranges.
No. 104 Worthless.

a more or less definite height would find easy escape to the surface of the ground. Flatness at the lower end may indicate perched water-tables.

As a further check of the reliability of this study, all of the records as translated to common terms by means of the final rating-curve were plotted against time. To facilitate comparison a similar plot of the index was traced on vellum and placed over the curve for each of the individual wells. This comparison showed at once any unduly erratic behavior and at the same time permitted still another opportunity to judge the suitability of the well. Certain outstanding characteristics such as flashiness or sluggishness, etc., could easily be seen, and in this way an excellent diagnosis of the ills and virtues of each well could be made. Based upon the results of the final inspection, weights to be used in striking a weighted average were assigned so that the more reliable wells could have the greater influence.

Still another factor which should be considered in the final analysis is the geographic distribution (Fig. 4). Clearly, if one portion of the drainage-basin were too well represented at the expense of the others, the composite would not be representative of the general change in ground-water storage for the river-system as a whole. In some cases it was found that two wells happened to be rather close together, and therefore care was taken that the weights finally assigned to the several records in the final average were discounted when reports from both members of a pair were available for the same time.

The final index, now available for hydrologists who wish to study any relations with stream-flow, is a weighted average of the translated reports from the wells indicated by the solid circles in the drainage-basin sketch of Figure 4. The open circles are the wells which had to be discarded for the reasons noted.

In conclusion it may be stated that although the analysis given these data is obviously more laborious than a straight averaging of the reports, there is greater assurance that the final results will not be misleading if the data are to be used for important comparisons with river-flow, or with the results of excessive pumping, and other phenomena.

Since this study was completed the data thus derived have been used in connection with the flow-records of the Susquehanna to determine the relation between ground-water elevation and the assured flow of the river for a number of weeks following. It is believed that reliable forecasts can now be made of the flow that will be equalled or exceeded for sufficient time in advance to be of practical value.

Pennsylvania Water and Power Company,
Baltimore, Maryland

DISCUSSION

R. C. BAKER (U. S. Geological Survey, Washington, D. C.)--In his paper Mr. MERRIAM has used a new method to make a ground-water index for several wells scattered over a wide area. This method of making up an index eliminates some of the faults of a straight arithmetic average. One important advantage is that wells can be added to or subtracted from the group without materially shifting the index, whereas only an average well can be added to or dropped from a group combined by means of an arithmetic average without changing the average. Another advantage of the suggested index is that fluctuations in individual wells do not change it as much as they would an arithmetic average.

When he makes an index, Mr. MERRIAM gets a curved line for each well which shows the individual characteristics of the fluctuation of water-level in that well compared with the index of all of the wells. It is on the basis of these lines that he eliminates those wells that show unusual fluctuations. Most of these wells are maintained by the Federal Geological Survey in cooperation with the Pennsylvania Department of Internal Affairs and are measured under my supervision. I have found this information of value when inspecting some of these wells in the field, because by knowing the nature of the fluctuation of the water-level I could study the natural conditions around the well and in some instances could explain its type of fluctuation.

Mr. MERRIAM has recognized that over a large drainage-basin there should be variations in the fluctuation of water-level in different wells. Nevertheless, he has eliminated from his index some wells which have unusual fluctuations and do not conform to the index. The selection of wells for the averages would depend somewhat upon the use to be made of the averages. The

author's interest is in wells showing effluent seepage and therefore stream-flow. The wells with unusual variations may represent true conditions over important parts of the area and should perhaps have proportionate effects on the index. I do not believe that Mr. MERRIAM is justified in eliminating any well from the group used in his index because it has unusual fluctuations until an examination of the well has shown it valueless to the index because of some special condition or until it has been proven that the index conforms better to stream-flow when measurements from the well are not included in the group. At best the wells included in the study are merely samples of the ground-water conditions on the watershed. A study of the geologic and hydrologic conditions over the watershed, particularly near the wells, should be made to improve the sampling procedure. This information should be considered before wells are added or dropped from the group and it should be used particularly to weight the data from different wells in respect to the effective productivity of the formations in which the wells are located.

The author has achieved much refinement in the analysis of the data available to him and has made a valuable contribution to the problem of molding data from wells scattered over a large area. Many of the disadvantages of an arithmetic average have been eliminated and I think the proposed index indicates ground-water conditions better than other averages based on the same water-level data.

R. M. LEGGETTE (U. S. Geological Survey, Jamaica, New York; communicated)--Mr. MERRIAM'S method of determining average ground-water levels in a drainage-basin is apparently used for the purpose of relating this important factor to the low flow of the major stream. His method in part is directed at overcoming difficulties resulting from new wells being added to the observation-program, old wells being deleted, or when records are unavoidably missing. Such difficulties must be overcome in any method used for averaging ground-water levels, particularly if observations are available for only a small number of wells.

Fluctuations of the water-table represent changes in the amount of water in storage in a ground-water reservoir, and this in turn determines largely the low flow of streams. In attempting to obtain an average value for ground-water levels in a large area such as the Susquehanna Basin, it is important, insofar as possible, that due weight be given to each part of the area in which controlling factors differ. It is generally not sufficient merely to give weight to one factor, such as good geographic distribution of observation-wells. Thus, an approximate determination of the average ground-water level in a large drainage-basin must be based on observations in wells so located that at least some weight is given to differences in geology, topography, recharge, discharge, etc. It is largely the result of differences in these factors that fluctuations of ground-water level are so dissimilar from place to place. Hydrographs for individual observation-wells do not in themselves provide a basis that justifies discarding the records of any one well merely because it does not conform with a few other hydrographs that happen to be available. With the exception of wells that are clogged, wells that receive surface-drainage during storms, and other obviously unsatisfactory observation-wells, peculiarities of individual hydrographs are chiefly the result of difference in such factors as those mentioned above. However, these fluctuations are real and represent changes in storage of the ground-water reservoir. The problem of determining a value for average ground-water level is therefore largely one of properly weighting the records that are available. This problem is not satisfactorily met by discarding those records that do not conform to the average of other arbitrarily chosen records. The discarding of such records is merely assigning zero-weight to them. If the records so discarded are representative of a considerable part of the drainage-basin, the value for average water-level may be considerably in error for the basin as a whole.

A study of the records of the wells used by Mr. MERRIAM in obtaining his values for average water-level shows that almost all of these wells are located in valleys or near valleys. Thus, although the wells are fairly well scattered over the drainage-basin, most of them are in areas of similar topography where one would expect somewhat similar conditions of geology and hydrology. Moreover, by far the larger part of the drainage-basin (the inter-stream or upland areas) is but little represented by the wells that he uses. His results, therefore, although perhaps representative of lowland- or valley-areas, may be considerably in error for the drainage-basin as a whole. It is of course recognized that in humid areas the factors of the hydrologic cycle are such that almost any group of observation-wells will give average results which show high ground-water levels in the spring and low ground-water levels in the fall. Such records no doubt will show some sort of relation between the high stage of the water-table each spring and the low flow of streams in subsequent months, and this relation, even though crude, may aid considerably in forecasting the approximate low flow of streams. However, it is believed that the number and distribution of observation-wells used by Mr. MERRIAM, together with his procedure in discarding records that do not conform with the other available records (mostly wells located in valleys) gives results that may not indicate very closely the changes in ground-water storage that have taken place in the Susquehanna Basin.

MONTHLY EVAPO-TRANSPIRATION LOSSES FROM NATURAL DRAINAGE-BASINS

W. B. Langbein

(Published with the approval of the Director, Geological Survey, United States Department of the Interior)

With limited restrictions the hydrologic cycle in a given area may be expressed essentially as follows: $P = (R + E + \Delta Fm)$ in which P represents the precipitation during a given period, R that portion which has reached or will reach the stream-channel either through surface or sub-surface paths, E that part which is evaporated from land and water surfaces and transpired by vegetation during the same period, and ΔFm the change in field-moisture content during the period. In general both E and Fm are unknown. When the period of time considered in the above expression is long, ΔFm may be neglected and then the evapo-transpiration losses equal the difference between P (rainfall) and R (runoff) [see 1 of "References" at end of paper]; on the other hand, when the period of time considered is short and considerable rain has fallen then E may be neglected and ΔFm equals the difference between P and R represents water stored as an increment to field-moisture to be disposed of by evapo-transpiration during subsequent rainless periods [2].

As explained by THORNTHWAITE, the return of precipitated water to the atmosphere through the processes of evaporation and transpiration is an important part of the hydrologic cycle [3]. MEYER [4] described transpiration essentially as a process of evaporation and conforming to the laws of evaporation but differing to the extent that the opportunity for evaporation is governed by the relatively sensitive character of plant-life, as for example the cessation of transpiration during the freezing-season, and the decrease of transpiration under conditions beyond the optimum for growth in a given climatic region (such as excessive temperature or too much water).

In general, however, for analysis of the hydrologic cycle, the evapo-transpiration losses may be grouped together and related to the following factors:

(1) The evaporating power of the atmosphere
(2) The amount of water available for evaporation
(3) The evaporation-opportunity, which depends on the distribution and position of the water relative to the atmosphere; the areal extent, type, and density of vegetation are important items in this factor

A critical survey of the evaporation of water would probably disclose differing rates of evaporation from every particle. For example, after the cessation of rainfall, the water that has been caught by leaf-surfaces is in a position exceedingly favorable for rapid evaporation whereas the deeper field-moisture is in a less favorable position relative to the moisture-absorbing atmosphere. Moreover, water that is insulated from the ground-surface by a zone that contains no capillary water is safe from direct evaporation.

Unfortunately no basin-wide direct measurements of evaporation and transpiration are available that would allow the derivation of relations between it and other meteorologic factors. Nor are there basin-wide measurements of field-moisture generally available that would permit the evaluation of the evapo-transpiration losses by solution of the hydrologic equation; as a result determination of the areal evaporation requires consideration of other conditions in addition to the hydrologic equation cited above.

In the absence of such direct measurements a rigorous solution is impossible but the following assumptions are suggested for employment in conjunction with the hydrologic equation to estimate the evapo-transpiration losses.

(1) That the rate of evapo-transpiration losses is proportional to the evaporating power of the atmosphere (evaporativity).
(2) That the rate of losses is directly related to the volume of field-moisture (including water on the ground and vegetal surfaces) existing at a given time.
(3) That the volume of field-moisture is related to the rate of base-flow.

The third assumption conforms to similar procedure used by SNYDER [2]. Base-flow, composed largely of effluent from ground-water may reflect in some degree soil-moisture conditions in the following manner. A high rate of base-flow is generally indicative of a high ground-water table. But recharge to ground-water takes place at a rate proportionate to the quantity of water in the zone of aeration. For example, a perfectly dry soil would permit little if any recharge, for it would absorb moisture; on the other hand, a soil at capillary capacity would transmit all excess or

Table 1--Derivation of field-moisture base-flow relationship, based on months having large net change in base-flow, Peace Creek at Arcadia, Florida

Month	(P - r)	Base-flow at beginning and end of month	Evaporativity	First approximation		Second approximation		
				First est. of losses = 0.65 × evaporation	Change in Fm	Av. Fm from first approx. graph	Second estimate of losses	Change in Fm
	in	cfs	in	in	in	in	in	in
Oct, 1931	2.09	1,300 249	5.9	3.8	-1.7	5.5	4.1	-2.0
Nov, 1931	0.06	249 83	5.8	3.8	-3.7	1.5	2.8	-2.7
May, 1932	7.08	62 260	7.7	5.0	+2.1	1.2	3.6	+3.5
Aug, 1932	5.50	180 650	5.4	3.5	+2.0	3.8	3.1	+2.4
July, 1933	9.27	412 2,370	5.7	3.7	+5.6	7.2	4.8	+4.5
Aug, 1933	3.65	2,370 1,715	5.8	3.8	-0.15	9.5	6.0	-2.35
Oct, 1933	1.26	2,260 625	6.5	4.2	-2.9	7.2	5.5	-4.3
June, 1934	9.30	700 3,225	5.6	3.6	+5.7	8.7	5.4	+3.9
Oct, 1934	0.88	1,470 296	6.3	4.1	-3.2	5.9	4.5	-3.6
Oct, 1935	1.51	1,950 527	5.7	3.7	-2.2	7.2	4.8	-3.3
Mar, 1936	2.29	2,475 985	4.6	4.6	-2.3	8.6	4.5	-2.2
June, 1936	7.72	240 1,025	6.4	4.1	+3.6	4.8	4.1	+3.6
July, 1937	7.77	422 1,000	6.3	4.1	+3.7	5.7	4.4	+3.4

gravity water to the ground-water. Hence the moisture-condition of the zone of aeration tends to regulate in some degree the proportion of the water that has infiltrated below the surface of the ground to reach the ground-water table.

During dry-weather periods the soil-water in the zone of aeration is removed by the processes of evapo-transpiration while the ground-water is drained into the stream-channels (except to the extent that part of the ground-water may be transpired by plants whose roots are in the capillary fringe or penetrate the ground-water table). Ground-water and soil-water drainage may proceed at differing rates and accordingly the relation between them may become quite tenuous. Moreover, it might be expected that light rains may moisten the surface-soil with no water reaching below the root-zone or the ground-water. While the ground is frozen, no relation can be expected to exist between the water in the zone of aeration and the base-flow.

The method suggested by these assumptions is illustrated with reference to two basins, namely, Skunk River Basin above Ames, Iowa (320 square miles), located in a sub-humid temperate area, and Peace Creek Basin above Arcadia, Florida (1,330 square miles), located in a humid sub-tropical region.

A tabulation of monthly mean areal precipitation was first prepared based on available Weather-Bureau rain-gages. Monthly runoff was determined by the stream gaging-stations of the United States Geological Survey. By hydrographic methods river-discharge was divided into base-flow and direct runoff, and each was adjusted for the difference in storage. Thus the volume of monthly base-flow during the month was adjusted for the difference in base-flow (or ground-water) storage between the first and last of the month, and similarly monthly direct runoff was adjusted for gain or loss in channel-storage during the month [5]. This adjustment was especially necessary for Peace Creek Basin where channel-storage volumes are significant. Total monthly runoff for any calendar month equalled the sum of the monthly base-flow so adjusted and the adjusted direct runoff. The difference between mean areal precipitation and total monthly runoff (always positive if data are correct) is equal to the sum of evapo-transpiration losses and gain or loss in field-moisture.

Table 2--Computation of monthly losses during months of little net change in base-flow, group of months in which base-flow is less than 300 cfs, Peace Creek at Arcadia, Florida

Month	(P - r)	Base-flow at beginning and end of month	Fm at beginning and end of month[a]	Change in Fm	Loss	Evaporativity	Average Fm
	in	cfs	in	in	in	in	in
Dec, 1931	1.43	83 90	0.1 0.3	0.2	1.23	3.0	0.2
Jan, 1932	1.22	90 94	0.3 0.4	0.1	1.12	4.5	0.35
Feb, 1932	0.14	74 76	-0.2 -0.2	0.0	0.14	4.4	-0.2
Mar, 1932	2.55	76 84	-0.2 0.1	0.3	2.25	5.6	-0.05
Jan, 1933	1.22	106 100	0.6 0.55	-0.05	1.27	2.9	0.58
Feb, 1933	2.38	100 96	0.55 0.50	-0.05	2.43	3.7	0.52
May, 1933	3.27	130 140	1.2 1.4	0.2	3.07	6.8	1.3
Jan, 1934	1.13	202 210	2.4 2.5	0.1	1.03	3.6	2.45
May, 1936	2.37	260 240	3.1 2.9	-0.2	2.57	7.7	3.0
June, 1937	8.47	230 422	2.8 4.5	1.7	6.77	7.1	3.6
Dec, 1936	1.64	253 260	3.0 3.1	0.1	1.54	2.3	3.0
July, 1932	3.35	225 180	2.7 2.1	-0.6	3.95	8.0	2.4
May, 1935	3.80	100 87	0.55 0.20	-0.35	4.15	8.2	0.4
Totals	32.97	4,008	34.9	+1.45	31.42	67.8	17.5
Average	2.53	154	1.34	.....	2.45	5.2	1.34

[a]From first approximate curve shown on left-hand side of Figure 1.

Note: These computations were repeated using the final curve shown on Figure 3.

As a preliminary step the relationship between base-flow and field-moisture in each basin was investigated. A table was prepared (see Table 1) listing those months during which large net changes (either plus or minus) in base-flow discharge occurred. The following data were listed: (1) Precipitation minus total runoff; (2) evaporativity (equal to evaporation from a Class-A pan in the basin); (3) estimated losses; (4) estimated field-moisture change (equal to precipitation minus total runoff minus estimated losses); and (5) base-flow at the beginning and at the end of the month. As a first approximation, losses (item 3) were estimated by multiplying the evaporativity for the given month (item 2) by the average ratio between total losses during the period of record and the total evaporativity (0.55 in the Skunk River Basin and 0.65 in the Peace Creek Basin). From these data, a preliminary curve was prepared showing total field-moisture corresponding to rates of base-flow (see left-hand part of Fig. 3). The scale of field-moisture was arbitrary, since only changes are significant.

A second table was then prepared listing the months whose average ground-water discharge was below 20 second-feet in the Skunk River Basin and below 300 second-feet in the Peace Creek Basin and in which but little net change in ground-water occurred (see Table 2, for example). The Table listed the following: (1) Precipitation minus total runoff; (2) base-flow at beginning and at end of the month; (3) field-moisture at the beginning and end of month corresponding to the preliminary curve plotted from the preceding analysis; (4) change in field-moisture during the month; (5) computed monthly losses being the precipitation minus total runoff minus (algebraically) the change in field-moisture; (6) the evaporativity; and (7) average of the field-moisture at the beginning and at the end of the month. The losses during the months listed in the Table were added and the average computed. The average field-moisture and the average evaporativity were also computed. Similar studies were made of months having mean base-flow between 20 and 100 second-feet and a table of those above 100 second-feet in the Skunk River Basin, and between 300 and 900 second-feet and over 900 second feet in the Peace Creek Basin, care being taken to use months in

which but little change in base-flow took place, so that the corrections needed for change in field-moisture were kept at a minimum, and to use as many months in which an increase in field-moisture was indicated as those in which a decrement was indicated.

Three groups of months for each basin were therefore averaged, giving average rate of losses for conditions of low, medium, and high base-flow. Thus three points of known evaporativity, monthly losses and field-moisture were available for each basin corresponding to these three groups. The points were plotted and tentatively straight lines were drawn to conform with these points, converging at the origin, so as to indicate zero water-losses with zero-evaporativity. These preliminary graphs were then used to recompute the values of losses originally used to derive the tentative curves showing a relation between base-flow and field-moisture (see Table 1). The revisions in the curve for Skunk River were minor, for Peace Creek small changes were needed; the second approximate curve is shown on the right-hand part of Figure 3 for Peace Creek and on Figure 1 for Skunk River.

Using the second approximate curve shown on Figure 3 for Peace Creek Basin, the process of

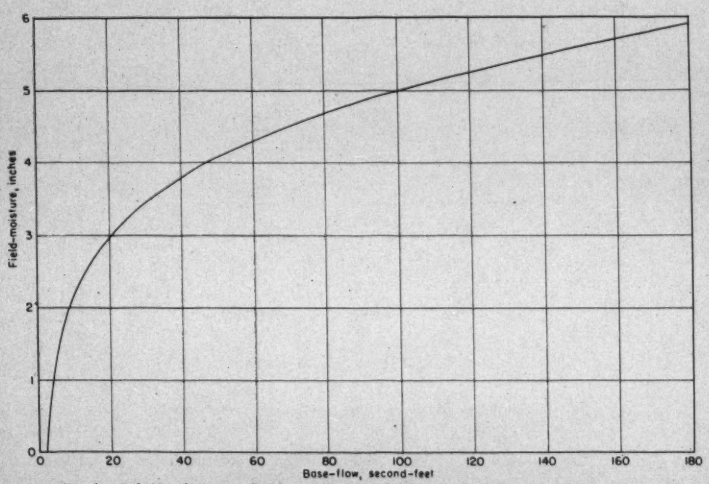

Fig. 1--Relation between field-moisture and base-flow, for non-winter periods, Skunk River above Ames, Iowa

computing monthly evaporation-transpiration losses was repeated. The number of groups were now increased as follows: First, groups of months having respectively low, medium, and high base-flow but little change, as in the first computation; secondly, all Januarys, all Februarys, all Marchs, etc.; and thirdly, a grouping of cold-wet months, and a grouping of hot-dry months. In this way all conditions received consideration. The final points and curve are shown on Figure 4. Similar groupings were made for Skunk River, except that the winter months were excluded. The points are shown on Figure 2 where they confirm the tentative straight lines. The points shown are for averages of groups of months, and the correlation is better than would be indicated for single months.

Figures 2 and 4 show the variation in rate of evaporation-transpiration losses with evaporativity and demonstrate the influence of the amount of field-moisture on the rate of losses. The Skunk River data seem to indicate that for a given field-moisture, losses are in simple proportion to evaporativity whereas the Peace Creek data indicate that the relationship is better defined by a graph curved as shown. It is assumed in both examples that there are no losses when evaporativity is zero.

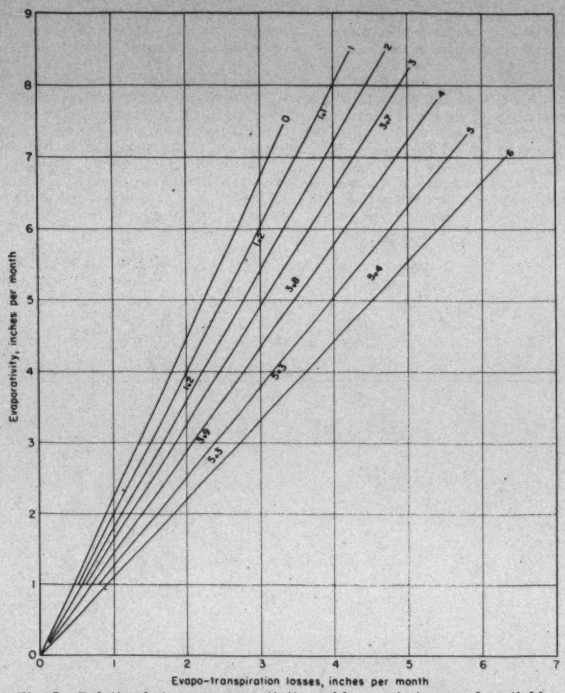

Fig. 2--Relation between evaporativity and losses in terms of available field-moisture, Skunk River above Ames, Iowa

Variation in rate of losses for a constant evaporativity is shown on Figure 5. Using an evaporativity of six inches per month, Figure 5 indicates that losses increase about linearly with field-moisture. The coincidence of the Peace Creek and Skunk River graphs has no significance since the selection of the origin of zero field-moisture was arbitrary. The slope of lines is believed, however, to be significant. On Figure 5 is also shown a graph obtained from published measurements [6] of the loss by evapo-transpiration from a brush-covered plot in Devils Canyon in southern California, during the rainless summer season, by measuring moisture in the soil to a depth of 20 feet (roots were 16 feet deep). Study of the data indicated (1) that evapo-transpiration ceased when moisture was depleted to eight or nine inches (wilting-point?) and moisture-content remained constant, (2) that evapo-transpiration losses varied about linearly as the evaporativity for a constant field-moisture, and (3) that for a given evaporativity the losses varied linearly with the volume of moisture in excess of eight inches. Figure 5 shows the variation between field-moisture in excess of eight inches and losses for an evaporativity of six inches per month. This line closely parallels that for Skunk River and Peace Creek, although that fact may be accidental. If losses can be assumed to cease when field-moisture decreases to zero-point, the origin for measuring field-moisture of Peace Creek and Skunk River should be increased by about four inches so that the graphs on Figure 5 may pass through the origin. However, the two graphs shown are for basin-wide conditions. Thus while losses may have ceased on higher portions of a basin remote from the stream-beds due to a lack of available moisture, transpiration and evaporation may be active along and near the stream-channels or lower parts of the basin. Hence it may

be difficult if not impossible to define a lower limit. Similarly during rainstorms capillary capacity of the soil making up the larger part of what is called "field-moisture" may be satisfied in the lower parts of the basin where the ground-water is at shallow depths, before the higher portions, and indeed, the soil in the higher parts where roots extend deep may never attain capillary capacity. In humid regions the upper limit may be approached after heavy rainstorms in the cool parts of the year. The range in field-moisture is probably greatest in southern California, where the rains during the winter build up the field-moisture, retained in the soil and rocks beneath, which are then completely drained out of the root-zone by evaporation and transpiration during the

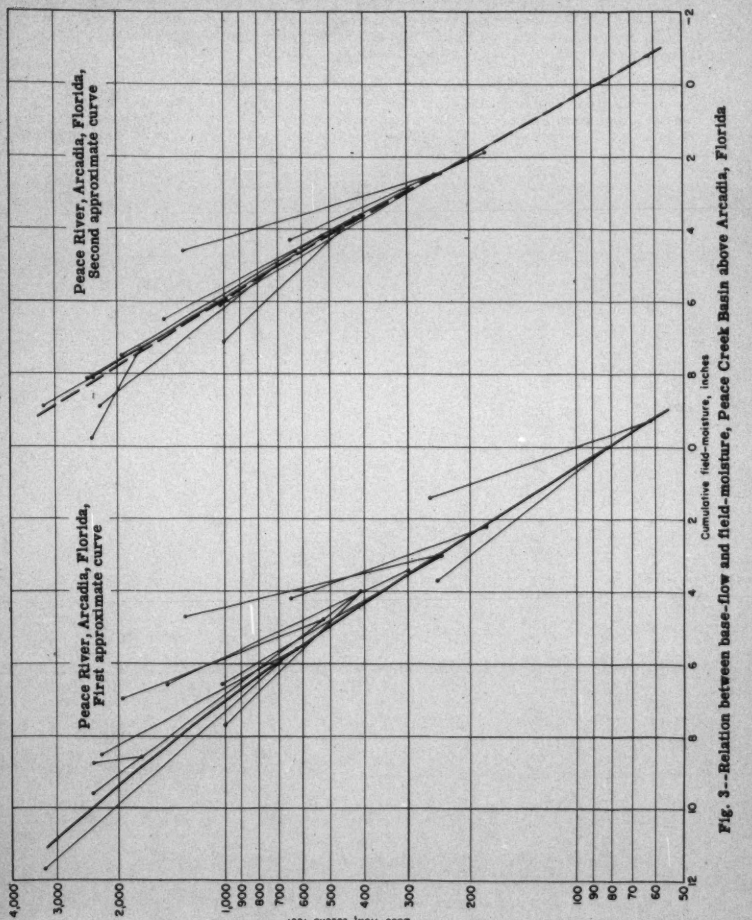

Fig. 3--Relation between base-flow and field-moisture, Peace Creek Basin above Arcadia, Florida

rainless summer season. Thus the range in measured field-moisture in the Devils Canyon Plot was from about eight inches to 22.3 inches, during the two seasons of experimentation (1928-30). During wet years the range is even greater.

Definitions

Field-moisture--Water retained in the basin above a zone of saturation is opposition to the downward pull of gravity. In this report it includes water on the vegetation and on the surface of the ground.

Evaporativity--The evaporating power of the atmosphere or the potential rate of evaporation with continuous water-supply [7]. In this report it is expressed in inches per month as determined by measurements of water-loss from an evaporation-pan.

Evapo-transpiration--A term embracing that portion of the precipitation returned to the air through direct evaporation or by the transpiration of vegetation, no attempt being made to distinguish between the two. Evapo-transpiration is called "water-loss" although from the point of view of the agriculturist this may be a misnomer since much of the so-called loss supports vegetation.

The computations of monthly mean areal precipitation, runoff and evaporativity, channel and

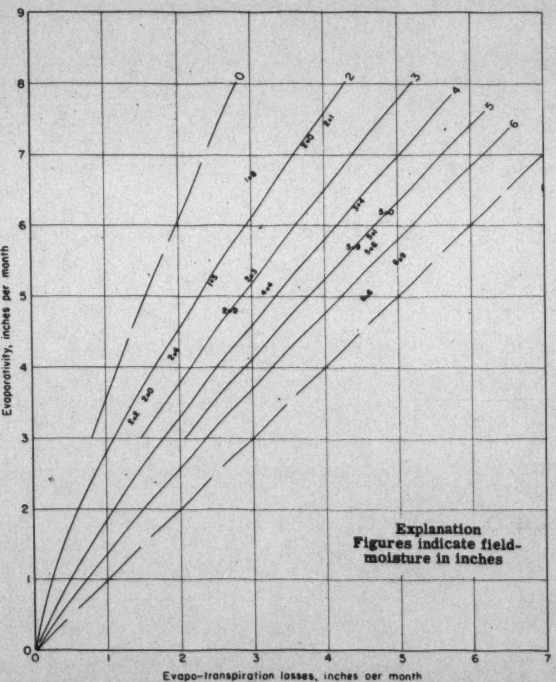

Fig. 4--Relation between monthly evaporativity and monthly losses in terms of field-moisture, Peace River at Arcadia, Florida

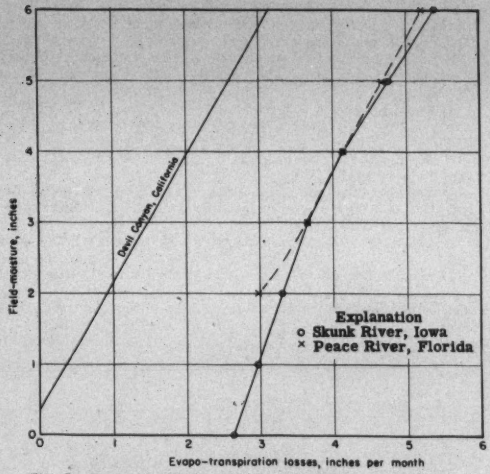

Fig. 5--Study of variation in rate of evapo-transpiration losses with field-moisture (evaporativity-constant = 6 inches per month)

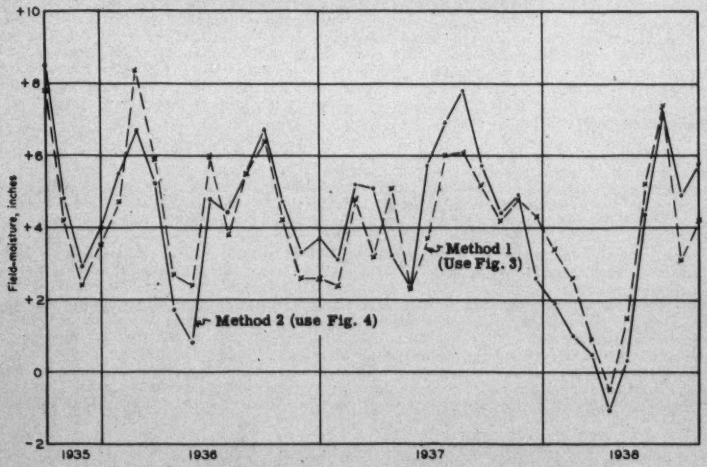

Fig. 6--Computed field-moisture, Peace Creek at Arcadia, Florida

base-flow storage-curves which made up the base data for this study, were prepared in the offices of the Geological Survey at Iowa City (Iowa) and at Ocala (Florida). The basic computations were carried out under the program on "Surveys of flood and droughts" of the Public Works Administration assigned to the Geological Survey. Without these basic computations the study described would not have been undertaken and the assistance of the staffs of the above offices is therefore gratefully acknowledged.

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U. S. Geological Survey,
Washington, D. C.

DISCUSSION

C. W. THORNTHWAITE (Soil Conservation Service, Washington, D. C.)--Four years ago KITTREDGE [see 3 of "References" at end of discussion], the Chairman of our Committee on Evaporation, prepared a map of the average annual water-losses to the atmosphere in the United States by computing the difference between precipitation and runoff, using the formula, $E = (P - R)$. Working independently, but using the same data and method, BAULIG [1] prepared a similar map of central and eastern United States. These maps are probably reasonably reliable because over a long period of time there is no significant change in the amount of water temporarily stored upon or beneath the surface. In order to make an accurate determination of evapo-transpiration losses for periods of a single year or less it becomes necessary to introduce a term for storage and the equation becomes $E = (P - R - Fm)$.

Precipitation and runoff over natural drainage-basins are measured by means of straightforward sampling techniques with a degree of accuracy that is known in a general way. The amount of water stored in a watershed in a given time-interval, on the other hand, cannot be measured by any existing technique, but must be determined by indirect means. Thus for the solution of his problem Mr. LANGBEIN has but a single equation that contains two unknowns.

He has proceeded in the only possible way when he attempted to relate the two unknowns in his equation to other measurable quantities. SNYDER [4] and GUTHE and OWEN [2] assume that there is a relation between the total volume of water stored in a watershed and the rate of base-flow, which latter can be computed from stream-gage records. LANGBEIN assumes further that the rate of evapo-transpiration loss from a drainage-basin is proportional to the volume of field-moisture and also to the rate of evaporation from a Weather Bureau Class-A evaporation-pan located within the basin. Both evapo-transpiration and field-moisture are unknown but the first is assumed to be proportional to the second and for any time-interval their sum must be a constant, equal to precipitation and runoff. Thus the problem is to vary evapo-transpiration until three factors of proportionality are found that give mutually consistent results. The equation is therefore

$$P = R - [f(E_p) \times f(\overline{BF})] - [f(BF_1) - f(BF_2)]$$

in which E_p is the evaporation from a pan, $\overline{BF}$ is mean base-flow, and BF_1 and BF_2 are rates of base-flow at the beginning and end of the period. This is an empirical approach but a justifiable one if it works.

On this point Mr. LANGBEIN'S paper is incomplete because there are no data to show whether

the procedure works or not. It would have been very easy with consecutive monthly values of precipitation, runoff, and pan-evaporation for three or four years to have computed the corresponding values of evapo-transpiration and field-moisture. It is entirely possible that ridiculous results might be obtained; for example, field-moisture increasing to impossibly large values if the computed losses to the atmosphere are systematically too low, or negative values of field-moisture if they are systematically too high.

It would be impossible to say without study to what extent reasonable results are dependent on the validity of the assumption that evapo-transpiration from a watershed bears some strict mathematical relation to losses from a pan. LANGBEIN'S assumptions regarding evapo-transpiration are similar to those of GUTHE and OWEN [2, Fig. 4, p. 802] relating evaporation from the soil to air-temperature and to the field-moisture that remains. Consideration of the physical factors involved will show that both of these basic assumptions must be very rough approximations only. Many of these empirical relations that appear to work do so because there is a small range of variation in the dependent variable for a large variation in the independent variable. Empirical studies of this sort cannot supplant the more fundamental studies that are addressed to the problem of making actual measurements of the transport of moisture from natural surfaces into the atmosphere, but there is ample justification to engage in them until such time as there is something better available.

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W. B. LANGBEIN (author's closure)--The graphs shown demonstrate a fairly consistent variation of losses with field-moisture and between field-moisture and base-flow. These demonstrations were the principal objectives of the paper. However, as Dr. THORNTHWAITE suggests the method of application may be as important as the derivation since results are often dependent on the method of use.

The writer introduced the following statements:

$$(P - R) = (E + Fm) \quad (1) \qquad E = f(E_p \times Fm) \quad (3)$$

$$Fm = f(B_f) \quad (2) \qquad Fm = (Fm_1 - Fm_2) \quad (4)$$

Dr. THORNTHWAITE has prepared a single equation which he offers as summarizing the above. If perfect correlation were obtained for each month of the record then Dr. THORNTHWAITE'S equation would be equivalent to the above. However, equation (1) must balance for each month, and Dr. THORNTHWAITE'S formula can only do that provided the coefficients are allowed to vary. To avoid this, the writer handles the problem as follows. Two methods of solution are available. Equation (1) is common to each of them. The first method uses equations (2) and (4). That is, base-flow directly corresponds to a volume of field-moisture (using relations such as shown on Fig. 1 or 3) and the change in Fm during a period is therefore known, and consequently E may be computed using equation (1). Obviously since field-moisture is directly functional with base-flow, no absurd accumulations in either the positive or negative directions can occur.

The second method uses equations (3) and (4) and is solved by a method similar to flood-routing. A non-freezing period when base-flow is stable is chosen, and the corresponding initial field-moisture is determined. Then a final amount of field-moisture for the month (or other period) is estimated and the mean during the month or period computed. Using this mean and the pan-evaporation, relations such as shown on Figure 2 or 4 are entered and the corresponding losses are determined. Using equation (1) the amount of change in field-moisture is computed and compared with the estimate. The estimate is revised until consistent results are obtained for the month. Generally only one revision is needed as the computations quickly converge on the answer. Then the next month is computed, and so on month to month. In general it might be stated that experience with this method indicated that the initial field-moisture used as the starting point may be varied considerably with but little effect on the computed value of field-moisture

Table 3--Sample computations of monthly field-moisture and losses, Peace Creek at Arcadia, Florida

Year	Month	(P - r)	Base-flow at end of month	Method 1		Method 2		
				Fm at end of month	Loss	Fm at end of month	Evapor-ativity	Loss
		in	sec-ft	in	in	in	in	in
			1,950	7.8		8.5		
1935	Oct.	1.51	527	4.2	5.1	4.8	5.7	5.2
	Nov.	0.76	235	2.4	2.6	2.9	4.3	2.7
	Dec.	2.70	385	3.5	1.6	4.0	3.0	1.6
1936	Jan.	3.61	638	4.7	2.4	5.5	3.1	2.1
	Feb.	4.32	2,475	8.3	0.7	6.7	3.7	3.1
	Mar.	2.29	985	5.9	4.7	5.2	4.6	3.8
	Apr.	1.30	260	2.7	4.5	1.7	7.1	4.8
	May	2.37	240	2.4	2.7	0.8	7.7	3.3
	June	7.72	1,025	6.0	4.1	4.8	6.4	3.7
	July	4.92	435	3.8	7.1	4.4	7.0	5.3
	Aug.	5.64	841	5.5	3.9	5.5	5.8	4.5
	Sep.	6.01	1,175	6.4	5.1	6.7	5.5	4.8
Totals and means		43.15	.....	-1.4	44.5	-1.8	63.9	44.9

several months later. According to equation (3), if the field-moisture is running high, computed losses are correspondingly high, which tends to reduce field-moisture unless, of course, (P - R) remains high. Conversely, if field-moisture is low, computed losses are low and computed field-moisture will increase, unless, of course, (P - R) remains low. Hence it has been found that ridiculous positive or negative accumulations of field-moisture are highly improbable by this method. When (P - R) is zero, Fm and rate of losses steadily decrease along a die-away curve.

On Figure 6 are comparisons between computations of field-moisture in Peace Creek Basin by Method 1 and by Method 2. Accumulations were begun in October, 1931, the beginning of stream-gaging at Arcadia), and the final three years of record available are shown to indicate the correspondence and to demonstrate that absurd accumulations did not occur. Sample computations are presented in Table 3.

The difference between the two graphs on Figure 2 is a measure of the inaccuracies in preparation of the graphs for Peace Creek and of the degree of correlation obtained. There was dispersion of points on both Figures 3 and 4 and hence the disagreement on Figure 6. If perfect conformance of the points was obtained on all graphs then a single equation containing the variables would balance perfectly each month. Neither of the two results is more correct than the other, since direct measures of field-moisture are not available. However, Method 2 minimizes the use of the relation between base-flow and field-moisture, which may be tenuous under certain conditions particularly during freezing-periods and may have merit on that account.

Fundamentally, fluctuations in field-moisture and losses are controlled by precipitation minus runoff (P - R) and given this quantity even crude estimates of losses might yield corresponding fluctuations in field-moisture. Therefore, the conformance shown on Figure 6 is not so much a check of the absolute values of losses or field-moisture but rather a demonstration of the degree of correlation with the basic assumptions. Doubtless other methods can be derived for solution, depending on the nature of the problem and of the kind of data available. There are two important objectives of this broader problem of evaluating field-moisture. One is the comparison of losses from different kinds of agricultural lands or perhaps measuring the fluctuations in field-moisture of lands under different use and the second is the derivation of a factor for expressing antecedent basin-wide condition for correlating storm-runoff with storm-rainfall. The first requires a precision that is probably not required of the second, and it is in such problems that empirical methods like the one described have a place.

HYDRAULIC CRITERIA FOR SAND-WAVES

W. B. Langbein

(Published with the approval of the Director, Geological Survey, United States Department of the Interior)

Sand-waves on rivers are rhythmic successions of waves which occur at flood-stages of streams heavily loaded with sediments. They take their name from the fact that sand and associated silts and gravels form a large part of the load transported by a river at such times. They seem to be peculiar to the Southwest and many vivid descriptions of them can be found in the literature of that region. R. C. PIERCE [see 1 of "References" at end of paper], who observed many sand-waves on the San Juan River in Utah, has described them as resembling in appearance "the waves thrown up by a stern-wheel river steamboat." He further describes their appearances as follows: "The sand-waves are not continuous, but follow a rhythmic movement. At one moment the stream is running smoothly for a distance of perhaps several hundred yards. Then suddenly a number of waves, usually from six to ten, appear. They reach their full size in a few seconds, flow for perhaps two or three minutes, then suddenly disappear. Often, for perhaps half a minute before disappearing, the crests of the waves go through a combing movement, accompanied by a roaring sound. On first appearance it seems that the wave-forms occupy fixed positions, but by watching them closely it is seen that they move slowly upstream. In the narrow parts of the stream the waves may reach nearly the width of the river, but in the wider parts they occupy smaller proportional widths. Usually they are at right-angles to the axis of the stream, but at some places, particularly in the wider parts of the river, they may suddenly assume a diagonal position, moving rather rapidly across the stream in the direction toward which the upstream side of the wave has turned." Many such descriptions may be found which in the main bear out PIERCE'S account, varying, however, as to size of wave, rate, and sometimes as to direction of movement.

Sand-waves are significant to the extent that they are associated with sediment-transportation during floods when so much of the changes in channels take place. Other influences of sand-waves on height of flooding are probably more or less secondary.

The rise and fall of water in stream-channels in response to rainfall or snow-melt is called a flood-wave and in comparison the sand-waves are strong local undular waves superimposed on the long flood-wave, brought about by hydraulic factors of slope, depth, velocity, and load. It is not believed that changed rates of discharge brought about by fluctuations in rainfall is the primary cause, although PIERCE states that sand-waves on the San Juan appeared in their best development on rapidly rising stages, nor is it likely that their occurrence affects the progress of the flood-wave in any significant degree, although their occurrence is indicative of a channel-condition that is of particular influence on the movement of the flood-wave. They are fairly common, yet exact reasons for their formation are still moot questions. It is possible that an examination of the hydraulic factors associated with such waves as reported by competent observers may aid in advancing an ultimate solution. Unfortunately, with one or two partial exceptions, quantitative information is lacking; all that is available is a visual description of the waves, somewhat as reported by PIERCE.

GILBERT [2] in his now classic researches on the transportation of debris by running water reported that he observed three phases of the transportation of debris.

"When the conditions are such that the bed-load is small, the bed is molded into hills, called dunes, which travel downstream. Their mode of advance is like that of eolian dunes, the current eroding their upstream faces and depositing the eroded material on the downstream faces. With any progressive change of conditions tending to increase the load, the dunes eventually disappear and the debris-surface becomes smooth. The smooth phase is in turn succeeded by a second rhythmic phase, in which a system of hills travel upstream. These are called antidunes, and their movement is accomplished by erosion on the downstream face and deposition on the upstream face. Both rhythms of debris movement are initiated by rhythms of water movement" [2, p. 11].

"Usually each antidune occupied the full width of the experiment trough; and in natural streams, so far as I have observed, they either reach from side to side of the channel or else form well-defined rows in the direction of the current. Not only is a row of antidunes a rhythm in itself, but it goes through a rhythmic fluctuation in activity, either oscillating about a mean condition or else developing paroxysmally on a plane stream-bed and then slowly declining. Paroxysmal increase starts at the downstream end of a row and travels upstream, gaining in force for a time, and the climax is accompanied by a combing of wave crests. Where the debris is very coarse, as on the outwash plains of glaciers, a din of clashing bowlders is added to the roar of the water" [2, pp. 31-32].

These descriptions of the antidyne phase greatly resemble those of some types of sand-waves frequently observed in rivers. GILBERT'S experiments on load, slope, grade of sediment, depth, and discharges provide a means for determining the hydraulic conditions that are necessary for the formation of antidunes, with the possibility that the results may have application to studies of sand-waves in rivers.

Criteria for antidunes--GILBERT observed "the slopes at which the phases of traction change are lower for large streams than for small, and are lower for fine debris than for coarse."

Figure 1 shows for a single grain-size the phase of transportation in relation to the bed-slope and the product VR used as a measure of the "hydraulic size" of a stream. The latter product when divided by the kinematic viscosity is the REYNOLDS number and so becomes a measure of the viscous forces. The graph supports GILBERT by showing that lower bed-slopes for given changes in phase were associated with increase in the product VR.

However, slopes, as such, depend upon the friction-conditions peculiar to the experiment

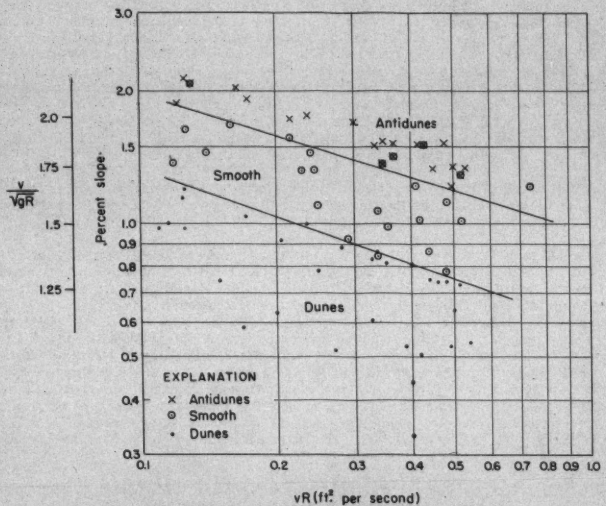

Fig. 1--Hydraulic criteria for phase of transportation of sediment, Gilbert's data, Grade C (0.50 mm)

trough GILBERT used.

To generalize the results on Figure 1, the slope should be multiplied by C^2 where C is the CHEZY friction-coefficient. But SC^2 according to the CHEZY equation is expressible in terms of velocity and depth which exist under the prevailing slope and friction. The ratio $(V/\sqrt{gR})$ so definable is dimensionless and is proportional to $\sqrt{SC^2/g}$. To define this proportionality a graph for each grade of sediment was plotted (not published) between the slope, S, for each run and the corresponding value of $(V/\sqrt{gR})$. The plotted points indicated a good relationship, which is shown as a secondary scale on Figure 1.

Figure 1 shows a scale along the vertical ordinate of $(V/\sqrt{gR})$ and the same conclusion made in regard to slope thereby applies in more generalized terms with reference to the kineticity $(V/\sqrt{gR})$.

DISCUSSION

J. W. JOHNSON (Soil Conservation Service, Washington, D. C.)--The author has developed the theoretical equation for the relation between the amount of suspended material in a stream and the physical characteristics of the bed and channel. Whether, for practical problems, this theoretical equation is superior to the functional relationship of LANE and KALINSKE or is of only academic interest is not indicated. The relationship of LANE and KALINSKE, however, appears to be satisfactory for the usual type of suspended-load calculation.

In discussion of the practical aspects of the problem of suspended-sediment transportation it is of interest to note that in certain streams, particularly those in the Piedmont Region of the Southeast, over 90 per cent of the stream-load has been found by direct measurement to consist of the very fine sediment-sizes--sizes that have values of t_c less than 0.020. Thus, the bulk of the load transported in these streams cannot be accurately predicted by either the LANE-KALINSKE function or the author's equation. Of practical importance, however, is that this very fine material is approximately uniformly distributed over the stream cross-section. Consequently, the load of this fine material at any instant can be estimated accurately from the analysis of a single sample.

Although the bulk of the sediment-load of certain streams may consist of very fine material moving almost entirely in suspension, the relatively small remaining part of the load that consists of coarse material may be, in some problems, the most important factor contributing to sedimentation-damages. For instance, flood-and-drainage damage caused by stream-channel aggradation appears to be primarily a bed-load problem involving the deposition of relatively coarse material. During low stages this coarse material moves by rolling or sliding along the bed, but during high stages part of it also moves in suspension. Direct measurement of the sediment-load of the Enoree River near Greenville, South Carolina, shows that as much as 50 per cent of the load of coarse material at some stages may move in suspension.

The relationship of LANE and KALINSKE is intended to permit estimates to be made of that part of the coarse material that moves in suspension. The part moving along the bed must be determined either by application of some bed-load formula or by direct measurement with a suitable trap. Bed-load formulas, in general, have been obtained from relatively small-scale flume-experiments in which velocities were rarely great enough to cause material also to move in suspension. Whether such formulas are valid in natural streams, where a considerable part of the load of coarse material is moving in suspension, is a problem that can be answered by the same type of laboratory experiment that is required to determine the functional relationships of the LANE-KALINSKE equation.

In regard to direct measurement of bed-load a portable measuring device has been developed at the Soil Conservation Service Sediment-Load Laboratory near Greenville, South Carolina, and has been used with considerable success on small streams with watersheds of three square miles and less. A larger unit no doubt could be constructed for use on larger streams.

SETTLING-VELOCITY AND FLUME-BEHAVIOR OF NON-SPHERICAL PARTICLES

W. C. Krumbein

Introduction

The importance of particle-shape in sediment-transportation has been pointed out by numerous writers. Comparatively few experimental data are available, however, and even these are partly confused by the use of two geometrically distinct shape-characteristics. Some writers emphasize the angularity of the corners and edges, whereas others emphasize the general form, that is, the ratios between length, breadth, and thickness of the particles. Most commonly both aspects are included in the same classification.

WADELL [1932, 1933] was the first to recognize the distinction between these two concepts of shape. He defined true sphericity as the ratio of the surface-area of a sphere of the same volume as the particle to the actual surface-area of the particle. Roundness was defined as the ratio of the average radius of the rounded corners and edges of a particle to the radius of the circle inscribed in the maximum cross-section of the particle. Both roundness and sphericity are non-dimensional numbers which vary from 0 to 1.

In his analysis WADELL [1934] showed that the coefficient of resistance of a given particle increases as its sphericity diminishes. He generalized his findings in terms of the probable behavior of various shaped particles during transportation. According to these generalizations sphericity should have a marked influence on transportation whereas roundness seems to be a second-order term in most instances. WADELL'S segregation of sphericity and roundness as two factors of shape resulted in a wide applicability of these concepts to the geological study of sediments. Sphericity has been found important in reconstructing the dynamic behavior of the particles, whereas roundness is a sensitive index to the abrasion suffered by the particle en route.

The present paper attempts to test the effect of shape on particle-transportation in flumes, and to relate this behavior to the settling-velocities of the particles. The data are confined to the bed-movement of single particles of different shapes, but the results show at least the order of magnitude of the shape-factor during stream-transportation, and indicate that in some instances this factor may be as important as size.

Choice of variables

Variables to be used in the study include properties of the fluid and of the particles, as well as characteristics of flow. The density, specific weight, viscosity, average velocity, and depth of water in the flume are important. Particle-properties include size, shape, and density. In this first approach shape is expressed in terms of sphericity and roundness. This choice results in the following items:

V = Mean velocity of the fluid (discharge/area)
y = Depth of fluid
γ_1 = Specific weight of fluid
ρ_1 = Density of fluid
μ = Dynamic viscosity of fluid
d = Nominal diameter of the particle, that is, the diameter of a sphere of the same volume as the particle
ρ_2 = Density of the particle
v = Velocity of the particle
ψ = Sphericity of the particle
P = Roundness of the particle

It is believed that dimensional analysis offers the most direct control in exploring the relations among these variables. Without such a guide or control the difficulty of deriving an analytical expression for the shape-factor would be immeasurably greater. Application of the Pi Theorem [ROUSE, 1938, pp. 13-18] combines the variables into a set of significant non-dimensional parameters which are convenient for experimental study. Moreover, use of the theorem reduces a complex problem to a study of the relations among a smaller number of combined variables.

Since it has been decided that there are ten physical quantities involved in the phenomenon under consideration, and since three fundamental physical dimensions are required to express them, seven non-dimensional parameters will be involved in the desired relation, according to BUCKINGHAM'S Pi Theorem. The algebraic process of determining the forms of these seven parameters will not be given here, since it has been described many times in the literature of the subject. Each of these parameters has a definite physical significance. The flow of water in the flume is characterized by one of these parameters called the FROUDE number, $F = (V/\sqrt{gy})$, which combines the average water-velocity, the depth, and the acceleration due to gravity, g. (This acceleration is the ratio of the specific weight to the density of the water.) The second parameter is the REYNOLDS number, $R = (Vy/\nu)$, where ν is the kinematic viscosity, $\nu = (\mu/\rho_1)$. Another parameter is the ratio of particle-velocity to mean water-velocity, (v/V). The fourth parameter is (d/y), which expresses the ratio of particle size to depth. The remaining non-dimensional parameters are the ratio of density of particle to fluid, (ρ_2/ρ_1), the sphericity, ψ, and the roundness, P.

The mathematical relation among the seven Pi terms may be expressed as follows:

$$f_1(V/\sqrt{gy},\ Vy/\nu,\ v/V,\ d/y,\ \rho_2/\rho_1,\ \psi,\ P) = 0 \qquad (1)$$

where f_1 signifies some unknown function. Of these seven combined variables, (v/V) is the dependent variable, and the others are the independent variables. In order to reduce the experimental difficulty, certain simplifications were introduced. The water-depth was kept constant, the particle-density was fixed, and the particle-volumes (and hence nominal diameters) were held

essentially constant. Because of the relatively high velocity used, the viscous effect was neglected. Finally, the effect of particle-roundness was arbitrarily considered to be secondary. (That it is negligible will be shown later.) The result of these simplifications is to reduce the flume-experiment to the determination of how (v/V) varies with sphericity as the FROUDE number changes:

$$(v/V) = C\, f_2(F, \psi) \qquad (2)$$

Here f_2 represents a functional relationship, and the variables held fixed are absorbed in the constant C.

The particles used in the experiments were made of cement mortar. They were of nearly constant volume and density, but the shape (sphericity) was varied systematically from one form to the next. WADELL [1934] had found that for practical purposes sphericity could be defined as in equation (3).

$$\psi = \sqrt[3]{\frac{\text{Volume of the particle}}{\text{Volume of circumscribing sphere}}} \qquad (3)$$

The volume of the particle is expressed in terms of its nominal diameter (d); the diameter of the circumscribing sphere in general coincides with the longest intercept (a) through the particle. By

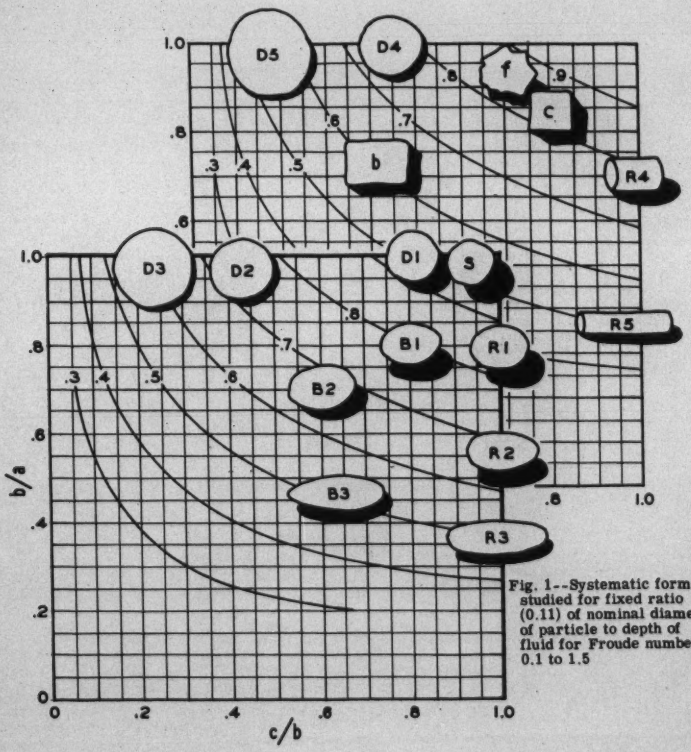

Fig. 1--Systematic forms studied for fixed ratio (0.11) of nominal diameter of particle to depth of fluid for Froude numbers 0.1 to 1.5

Table 1

Form	Symbol	Density	Nominal diameter	Sphericity, ψ	Approx. roundness, P	Critical Froude No., F_c	(v/V) for $F = 0.5$, $d/y = 0.11$	Settling velocity	Reynolds No., R	Coeff. resistance, C_D	Form-coeff. (V_1/V_3)
		gm/cc	cm					cm/sec			
"Spheres"	S	2.06	1.47	0.96	0.95	0.13	0.68	63.4	9300	0.50	0.91
Rollers 1	R1	2.14	1.44	0.85	0.90	0.15	0.64	53.0	7640	0.77	0.75
Rollers 2	R2	2.11	1.44	0.68	0.85	0.20	0.58	48.8	7030	0.87	0.69
Rollers 3	R3	2.02	1.46	0.52	0.80	0.35	0.50	39.1	5700	1.28	0.56
Disks 1	D1	2.12	1.43	0.93	0.95	0.16	0.61	51.8	7410	0.78	0.73
Disks 2	D2	2.03	1.45	0.75	0.95	0.37	0.52	35.7	5170	1.53	0.51
Disks 3	D3	2.13	1.46	0.61	0.95	0.42	0.38	24.1	3520	3.72	0.35
Blades 1	B1	2.09	1.43	0.80	0.85	0.20	0.59	49.1	7020	0.85	0.69
Blades 2	B2	2.07	1.44	0.68	0.80	0.33	0.54	39.7	5710	1.28	0.56
Blades 3	B3	2.15	1.43	0.52	0.75	0.41	0.46	34.5	4960	1.82	0.49
Cubes	C	2.14	1.45	0.82	0.25	0.31	0.56	46.7	6750	0.97	0.66
Fragments	f	2.08	1.45	0.85	0.20	0.26	0.54	46.0	6680	0.96	0.65
"Bricks"	b	2.10	1.44	0.65	0.25	0.40	0.39	33.6	48±0	1.84	0.47
Rollers 4	R4	2.24	1.44	0.82	0.30	0.18	0.62	51.6	7430	0.87	0.73
Rollers 5	R5	2.23	1.41	0.54	0.30	0.38	0.52	36.6	5160	1.69	0.51
Disks 4	D4	2.17	1.44	0.81	0.95	0.32	0.50	38.4	5540	1.46	0.53
Disks 5	D5	2.20	1.43	0.57	0.95	0.35	0.50	26.4	3760	3.26	0.37

substituting these volumes in equation (3), the sphericity becomes simply the ratio (d/a). The procedure used in the present study was a relation described by the writer [1941], in which it was shown that ψ could also be measured by using three mutually perpendicular intercepts through the particle. These are the longest, or a-axis, the intermediate, or b-axis, and the shortest, or c-axis. The relation between these intercepts and WADELL'S sphericity is:

$$\psi = \sqrt[3]{(b/a)^2\ (c/b)} \qquad (4)$$

By means of equation (4), lines of equal sphericity may be drawn on a graph having the non-dimensional axes (b/a) and (c/b). Two sets of forms were made by hand, one along certain systematic directions on such a graph, and the other a series of special forms which permitted some evaluation of the roundness-factor as well. Figure 1 shows the two sets of forms. The curved lines on the graphs are lines of equal sphericity. The ten forms superimposed on the lower-left graph include disks along the line (b/a) = 1, roller-shaped particles along the line (c/b) = 1, and blades (triaxial ellipsoids) diagonally across the chart. The tenth form (S) is approximately spherical, although limitations of hand molding, and differential shrinkage during drying resulted in an average sphericity of 0.96 instead of 1.00.

The second set of forms is shown in the upper-right graph. The rollers are right-cylinders, and the disks differ from the first set both in position and in the sharpness of their edges. The cubes (c) and "bricks" (b) are rectangular solids, and the fragments (f) represent particles of moderately high sphericity but almost zero-roundness. The width of the shadows in the drawings indicates roughly the thickness of the particles. The significant values of the 17 shapes are summarized in Table 1.

Flume-experiments

The behavior of the particles in running water was studied in a flume 22 feet long, 0.44 foot wide, and 0.96 foot deep. Flume and accessories were supported by steel rods with turn-buckles for adjusting the slope. Lines were painted across the bottom at five-foot intervals, to permit timing the particles as they moved along. Water was supplied through a stilling-basin from a constant-head tank, and discharge was measured with a 90° V-notch weir. A sediment trap was used to recover the particles.

The flume-observations were made in a control-section about 10 feet long, in which the depth was kept essentially constant at 0.43 foot. By adjusting discharge and tail-gate position it was possible to cover a range of FROUDE numbers from about 0.1 to 0.7 without changing the slope of the flume itself. For FROUDE numbers (F) above this the slope was adjusted slightly for each run.

The experimental procedure involved first establishing essentially uniform flow in a control-section. After this the individual particles were dropped into the water some distance upstream

from the first marker, and their progress timed with a stop-watch. Usually ten observations were made on each form at any one F, but occasional duplicate sets were measured. A detailed study was made of the ten systematic forms of Figure 1 at a fixed ratio (d/y) = 0.11, over a range of FROUDE numbers from 0.1 to 1.5. This represents a range in mean water-velocity from 0.45 to 5.5 feet/sec. Figure 2 shows the smoothed curves found by plotting (v/V) against F for various shapes. Actually the data scatter to an appreciable extent; the degree of scatter may be seen from the inset curve which gives the observed points for the most nearly spherical particles.

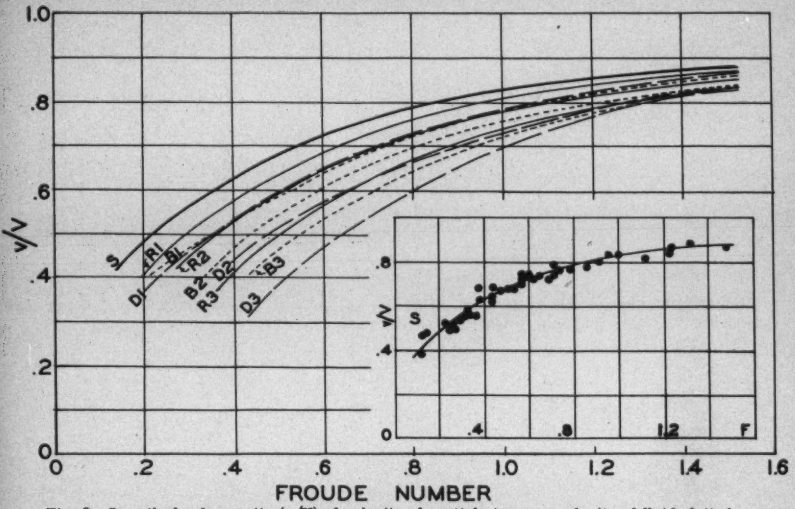

Fig. 2--Smoothed values ratio (v/V) of velocity of particle to mean velocity of fluid plotted against Froude numbers (F) for various shapes

The Figure shows that all the forms increase rapidly in their ratios of particle-velocity to water-velocity at low FROUDE numbers, and level off toward asymptotes between 0.8 and 0.9 at higher values of F. The spherical particles (S) have the highest ratio (v/V) of any form for a given F. Within each set of shapes (as disks or rollers) the higher sphericity form has the higher ratio. It may be noted, however, that sphericity is not the only controlling factor, because the curves of rollers of given sphericity lie noticeably higher than those of disks of similar sphericity.

Figure 2 is related to equation (2) in that it shows how (v/V) varies with F for different fixed values of ψ. The full implications of the curve of Figure 2 will not be considered in this paper, beyond mentioning that they approximately satisfy equations of the type $y = y_0(1 - e^{-ax})$, where y represents the ratio (v/V), and x is the FROUDE number. Tests of the data on semi-log paper indicate that the coefficient a varies with the shape from approximately 1.4 to 2.1. This variation is not large, however, and to a first approximation it may be said that the rate of change of (v/V) with respect to F is roughly the same over the range of F-values studied. This has a bearing on the geological interpretation of the shape-factor during transportation, because it suggests that the relative rate of movement of differently shaped particles may not change markedly over a moderate range of stream-velocities. Hence complexities in sediment-interpretation introduced by changes in relative velocity among different shapes are probably not of first-order importance.

The critical value of F at which motion began was determined for each of the 17 forms shown in Figure 1. At very low FROUDE numbers the particles rested quietly on the flume-bottom. As F increased, the particles first displayed an erratic movement, and then developed an increasingly steady motion. The critical F for each shape was taken as the average value at which the particles showed continuous movement through a five-foot test-section. This value varied somewhat

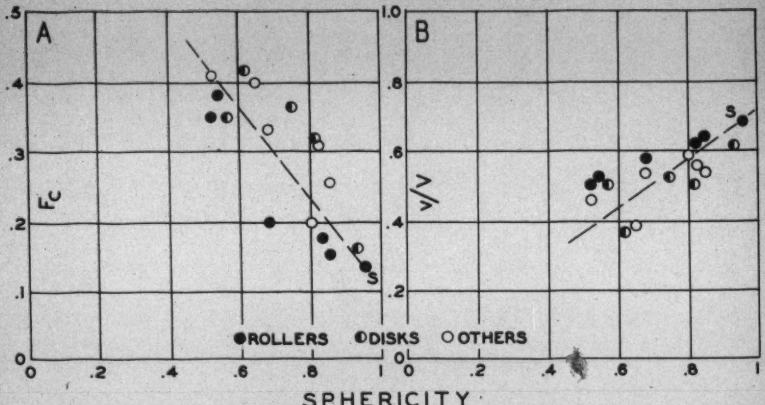

Fig. 3--(A) Critical Froude number, F_c, and sphericity and (B) ratio, v/V, of velocity of particle to mean velocity of fluid and sphericity, for fixed Froude number 0.5 and ratio of velocities 0.11 for rollers, disks, and other forms

even for the same shape, but despite the scatter of the data, it was found that particles of higher sphericity in general had lower critical values than less spherical particles. A detailed study was also made of all 17 forms at a fixed value F = 0.5. At this value all 17 shapes were moved, and hence the data represent the relative behavior of the forms under fixed conditions of F and of (d/y). The experimental data are given in Table 1.

Figure 3-A shows the critical FROUDE number, F_c, plotted against sphericity, and Figure 3-B shows the ratio (v/V) plotted against sphericity for the fixed conditions F = 0.5 and (d/y) = 0.11. Both of the graphs show a relation between flume-behavior and sphericity, although the data scatter appreciably. It may be seen that the rollers show consistently lower F_c-values than disks of corresponding sphericity, indicating that the rollers begin movement at lower FROUDE numbers. Similarly, at F = 0.5 the rollers have higher (v/V)-ratios than the corresponding disks, indicating that they move more rapidly under given conditions than disks of similar sphericity. Despite these difficulties in detail, the sphericity does give a first approximation to relative flume-behavior. The correlation-coefficient between ψ and F_c is -0.79, and that between ψ and (v/V) is 0.71. Both of these values are above the threshold-value of 0.61, which marks the 0.01-level of significance for the correlation-coefficient between pairs of 17 items [MILLS, 1938, p. 610].

Both Figures 3-A and 3-B support the thesis that roundness is a second-order factor in flume-behavior. The angular particles include the cubes, the bricks, and the fragments, as well as rollers 4 and 5, when WADELL'S definition is rigorously followed. These forms group themselves with others of corresponding sphericity along the main trend of points on the graphs. The only actual effect of roundness observed experimentally was by SHIELDS [1936], who found that during bed-load movement the angular particles required a greater force to set them in motion, but after motion was begun, they moved along at essentially the same rate as more rounded particles. The initial effect is presumably due to the greater ease of angular particles locking together in the bed.

Settling-velocity data

The experiments just described indicate that WADELL'S concept of sphericity is related to the dynamic behavior of various shaped particles, but apparently sphericity alone is not the controlling factor. In order to extend the study, the settling-velocities of the 17 forms were determined. The measurements were performed in a lucite pipe six inches in diameter and about six feet high, filled with water at 20°C. The particles were released in random position at the surface and were timed over a four-foot fall with a stop-watch. The upper marker was about two feet below the water-surface, to allow for initial accelerative effects [SCHILLER, 1932]. Average values

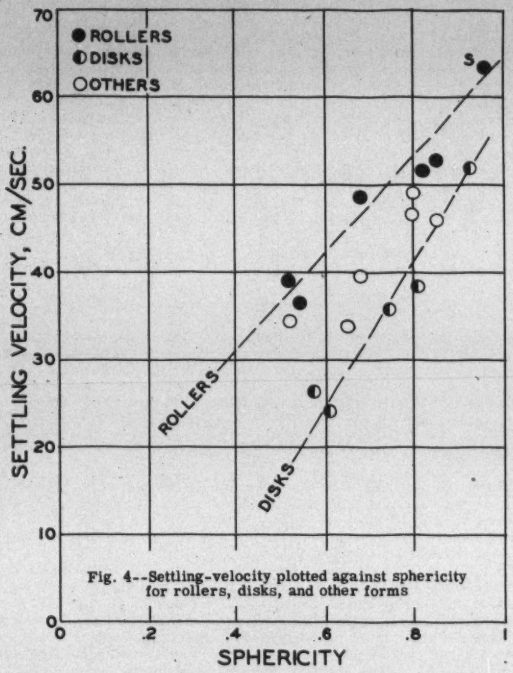

Fig. 4--Settling-velocity plotted against sphericity for rollers, disks, and other forms

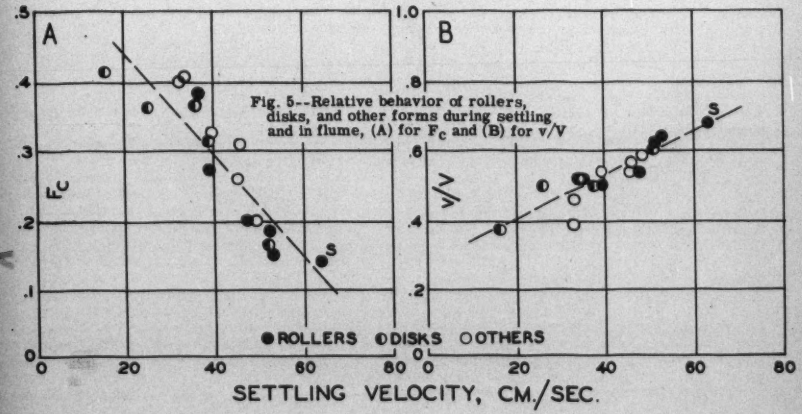

Fig. 5--Relative behavior of rollers, disks, and other forms during settling and in flume, (A) for F_C and (B) for v/V

were obtained, based on from 10 to 20 observations on each form.

The settling-velocity data are given in Table 1. Figure 4 shows the settling-velocity plotted against sphericity. Again the data scatter, but it may be seen that the rollers as a class have larger settling-velocities than corresponding disks, as indicated by the lines drawn through the points. The settling behavior of the several shapes in terms of sphericity thus displays a similar relation to the flume-behavior in terms of sphericity. WADELL himself [1934] found a similar situation in his study of settling-velocity data, in that roller-shaped particles generally had a higher settling-velocity than disks of the same sphericity class. He attributed this fact either to a failure of the practical sphericity equation (equation 3), or to the particles assuming an "easy shape position" during settling. In the present experiments it was found that the particles tended to orient themselves with their maximum cross-sections normal to the direction of settling, regardless of the position in which they were released at the water-surface. It seems likely from both the flume and settling-velocity data that the difference in behavior of rollers and disks is due to an additional factor in shape, not explicitly included in the sphericity. That the sphericity does furnish at least a first approximation to relative settling-velocity is shown by the correlation-coefficient of 0.76 between these two variables.

Settling-velocity as an index of flume-behavior

The close correspondence between the relative behavior of rollers and disks during settling and in the flume suggests that the settling-velocity itself may be an adequate index of relative flume-behavior. This was tested by plotting the settling-velocity against F_c and against (v/V) at F = 0.5. Figures 5-A and 5-B show the results; in both instances the degree of scatter, as compared to Figures 3-A and 3-B, is much reduced. More important, the order in which the successive values occur is almost a 1:1 correspondence between the flume-data and the settling-velocity. For flume-studies of particle-transportation, therefore, the relative settling-velocities of the particles furnish an adequate index of relative flume-behavior.

It should be borne in mind that the present particles are all of essentially the same volume and density, so that in the experiments the settling-velocity reflects the influence of shape directly. In other instances, in which size and density as well as shape differ, the settling-velocity involves a composite of all three effects, and so does not isolate the shape-factor explicitly. However, settling-velocity may well serve as a general criterion of relative behavior during transportation. The principles underlying suspended-load transport were established by SCHMIDT [1925], and during the following decade they were extended by O'BRIEN [1933], LEIGHLY [1934], and CHRISTIANSEN [1935]. Experiments by ROUSE [1938] yielded the first quantitative check of settling-velocity effects in suspension. This work demonstrated that suspended-load transport of particles is a function of their settling-velocities. The present experiments show that the same principle applies to bed-movement of single particles. In suspension-transport settling-velocity is a basic factor, because this phenomenon is actually involved. In bed-movement it is not involved in the same way, but it may safely be said that the same properties (size, shape, density) are involved to essentially the same degree in both modes of transport.

The coefficient of resistance as a function of the REYNOLDS number

The purpose of the present study is to isolate the shape-factor independently of size and density. The close proportionality between settling-velocity and flume-behavior suggests that some single overall non-dimensional shape-factor may be derived from the settling-velocity, which may show explicitly to what extent shape influences hydrodynamic behavior. The development of such a shape-factor may be indicated by reconsidering the variables listed earlier.

In order to derive a form-factor from settling-velocity, the definition of v in the list of variables may be broadened to include either the velocity of the particle in a flume, or its settling-velocity in quiet water. Now by regrouping the original variables, other dimensionless terms than those already used may be obtained. For example, if the properties of the particle are taken to be of first importance, it is possible to define a "particle FROUDE number" which parallels the conventional FROUDE number in its structure. This particle FROUDE number can be related to the coefficient of resistance of particles moving through fluids. The particle FROUDE number has the form $F_p^2 = (V-v)^2/\{d[(\rho_2 - \rho_1)/\rho_1]g\}$, where the symbols have the meanings shown in the earlier list. In this expression $(V - v)$ represents relative velocity between fluid and particle. This applies even in quiet water, where V = 0, so that the numerator becomes simply v^2. The conventional expression for the coefficient of resistance during free fall is $C_D=(4/3)[(\rho_2 - \rho_1)/\rho_1]gd/v^2$. Substitution in these two expressions yields relation (5).

$$C_D = (4/3)\,(1/F_p^2) \qquad (5)$$

This definition identity indicates that the particle FROUDE number, derived from the Pi theorem, is simply another way of expressing the coefficient of resistance. This identity of one of the Pi-theorem parameters with the coefficient of resistance makes available to the present study two principles introduced by WADELL in 1934. He broadened the definition of the coefficient of resistance by substituting the nominal diameters of particles of any shape for the true diameter of a sphere, on which the original definition was based. This modification extended the usefulness of the concept without changing the already established values for true spheres. By applying his new definition to conventional graphs of the coefficient of resistance as a function of the REYNOLDS number [WIESELSBERGER, 1923; WADELL, 1934; ROUSE, 1937], WADELL derived two generalizations of basic importance in the study of the shape-factor:

(I) All particles of the same specific gravity, regardless of their volumes, shapes, or shape positions, have the same terminal settling-velocity in a given fluid if the ratio of the coefficient of resistance to the REYNOLDS number of the particles is constant.

(II) All particles of the same specific gravity settling in a given fluid, regardless of their shape, shape position, or terminal settling-velocity, have the same nominal diameter if the product of the coefficient of resistance and the square of the REYNOLDS number for the particles is constant.

These relations were shown by eliminating size and settling-velocity respectively by appropriate combinations of C_D and R. The ratio (C_D/R) eliminates the nominal diameter d and yields

$$(C_D/R) = (4/3)\,[(\rho_2 - \rho_1)/\rho_1]\; g\nu/v^3 \qquad (6)$$

When R is squared and multiplied by C_D, the v^2 cancels, yielding:

$$C_D R^2 = (4/3)\,[(\rho_2 - \rho_1)/\rho_1]\; gd^3/\nu^2 \qquad (7)$$

Inasmuch as the writer's forms were all of essentially the same volume and specific gravity, they should agree with WADELL'S second principle as given by equation (7). Figure 6 indicates that the relation holds satisfactorily. The graph is a logarithmic plot of the coefficient of resistance against the REYNOLDS number. The heavy line is the conventional curve for spheres taken from ROUSE [1937]. The present experimental points extend upward from this curve along a line whose slope is -2. The straight line was calculated from equation (7), which yielded $C_D R^2 = 43.7 \times 10^6$. By choosing $C_D = 0.42$, the corresponding value of R is 10,200. These two values represent a point on the main curve as shown. The slope of the line is obtained by considering the equation in the form $C_D = (\text{const.})/R^2$. By taking logs of both sides there results $\log C_D = -2 \log R + \log \text{const.}$ This curve has a slope of -2, which corresponds to an angle of about 64° from the horizontal.

WADELL'S first principle permits an evaluation of the shape-factor in terms of equivalent sizes of spheres. From equation (6) expressed as $C_D = (\text{const.})/R$, logs of both sides yield $\log C_D = \log R + \log \text{const.}$ Hence a line drawn on the graph of Figure 6 with a slope of 1 indicates all particles of the same settling-velocity in accordance with WADELL'S first principle. By projecting such a line from point D3 in Figure 6 (the dashed line) it is seen to intersect the curve for spheres at R = 520. This corresponds to a sphere of diameter 0.3 cm, and of the same density as the disk, settling under the same conditions. Thus a disk of nominal diameter 1.44 and sphericity 0.61 settles at the same rate as a sphere of the same material 0.3 cm in diameter. This is a ratio of nominal diameters of nearly 5 to 1. A practical consequence of this is that a mixture of disks and spheres (as mica flakes in sand) may yield through sieving two distinct grades separated by several WENTWORTH intervals, and yet represent particles which behave the same during settling.

The "form-coefficient"

WADELL'S principles permit the development of a non-dimensional shape-parameter which correlates very highly with flume-behavior. Reference to Figure 6 shows that any point representing a non-spherical particle (as D3 for example) has two points associated with it along the main curve for spheres. The REYNOLDS number of the particle itself is R_1, the point derived from the first principle has another value R_2, and the point derived from the second principle has the value R_3. Now let v_1, d_1 represent the settling-velocity and nominal diameter of the particle D3 itself. Then point R_2 on the graph represents a sphere of the same settling-velocity v_1 as the disk, but of different nominal diameter d_2. Here a combination of differences in nominal diameter

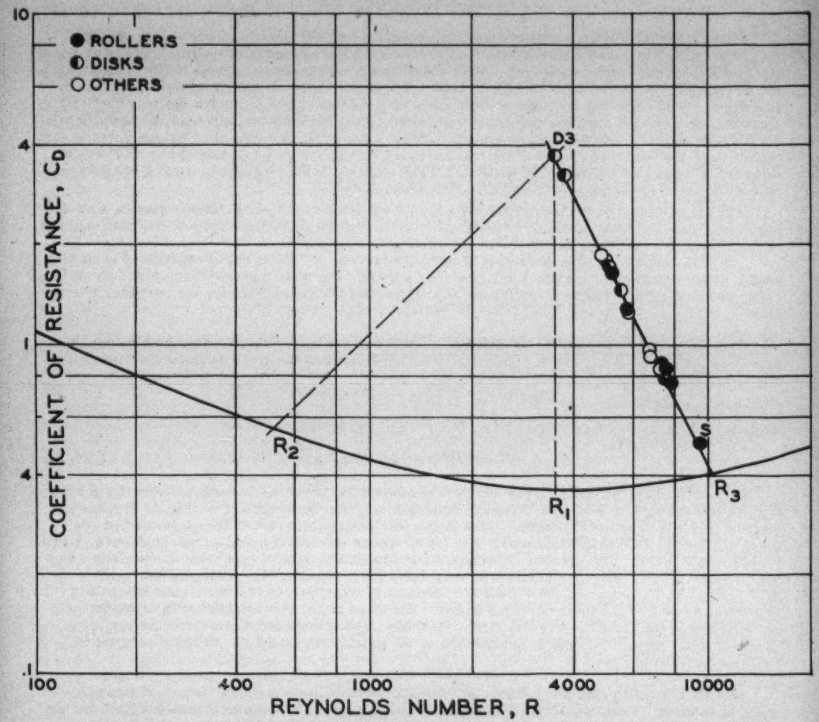

Fig. 6--Logarithmic plot of coefficient of resistance against Reynolds number, for rollers, disks, and other forms

and shape account for the same settling-velocity. Point R_3 on the graph represents a sphere of the same nominal diameter d_1 as the disk, but of different settling-velocity v_3. In this instance the difference in settling-velocity is due solely to the difference in form of the particles, because all other factors are constant. Hence the non-dimensional ratio (v_1/v_3) should be an overall index of form alone. This ratio may be called the "form-coefficient." Physically it represents the ratio of the actual settling-velocity of a particle to the settling-velocity of a true sphere of the same nominal diameter and specific gravity as the particle, settling in the same fluid. The form-coefficient accordingly, is a non-dimensional expression of the relative rate of settling of a given particle referred to the sphere derived from WADELL'S second principle.

It may be mentioned parenthetically that the ratios obtained above are equal to the ratios of the corresponding REYNOLDS numbers. Thus $R_1 = (v_1 d_1/\nu)$; $R_2 = (v_1 d_2/\nu)$; and $R_3 = (v_3 d_1/\nu)$. Actually, three ratios less than unity may be had from these values. They are $(R_2/R_1) = (d_2/d_1)$; $(R_1/R_3) = (v_1/v_3)$; and $(R_2/R_3) = (v_1 d_2/v_3 d_1)$. The ratio (R_2/R_1) represents a ratio of two nominal diameters derived from WADELL'S first principle. The ratio (R_1/R_3) represents a ratio of two velocities derived from WADELL'S second principle. This ratio is the form-coefficient. The ratio (R_2/R_3) is the ratio of the diameters and velocities of a sphere of the same settling-velocity as the particle to those of a sphere of the same nominal diameter as the particle.

The form-coefficient for all 17 shapes is given in Table 1. Figure 7-A and 7-B show this ratio plotted against the flume-data. In both graphs the degree of scatter is of the same general order as in Figure 5. The close relation between the form-coefficient and flume-behavior is borne out by the correlation-coefficients between the two. For Figure 7-A it is 0.91 and for 7-B it is -0.91.

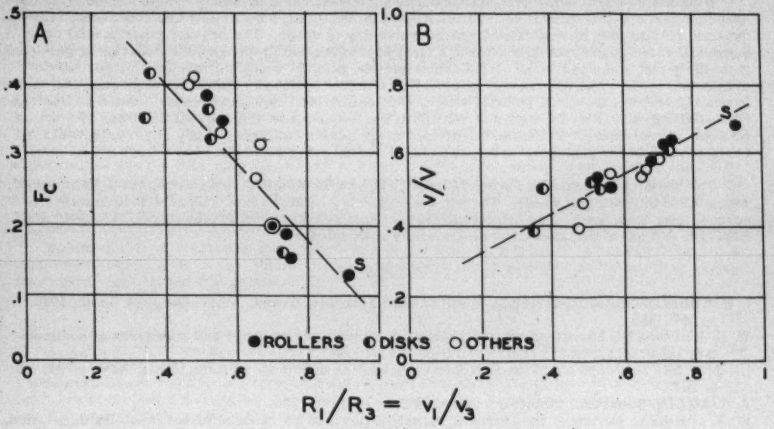

Fig. 7--Form-coefficient and flume-behavior, (A) for F_c and (B) for v/V, for rollers, disks, and other forms

Comparison of shape-concepts

As commonly used, the word "shape" refers to the overall geometrical form of a particle, regardless of size or composition. Two particles may therefore be said to have the same shape if they are geometrically similar, that is, if the ratios of their intercepts and the angles between the intercepts are the same for both particles. In the dynamic behavior of particles, however, decidedly different geometrical forms may behave in the same manner in fluids, so that shape may also be defined on a basis of dynamic similarity. WADELL introduced his concept of sphericity as a "sedimentological shape," referring to the essentially similar sedimentary behavior of particles having the same sphericity. Similarly, the "form-coefficient" is so named because particles of a given (v_1/v_3)-ratio have equal relative settling-velocities with respect to the corresponding spheres derived from WADELL'S second principle.

There has been a tendency in geology to express shape as the sphericity or an equivalent measure, and to consider roundness as a separate property. This tendency reflects a growing realization that a dynamic shape-concept is more significant in sedimentary problems than a strictly geometrical concept. In other sciences, however, geometrical similarity is still largely relied upon in shape-definitions, so that some confusion of terms is possible. Perhaps it would be preferable to use the term "geometrical shape" when geometrical similarity is intended. Sphericity and roundness may then be recognized as two factors isolated from the more general shape-concept. The writer's "form-coefficient" enters this classification as an overall shape-index based on similar settling-velocity behavior, regardless of geometrical form.

The fact that the form-coefficient affords a closer approximation to flume-behavior than sphericity probably means that the observable settling-velocity is more directly a factor in flume-behavior than the ratio of surface-areas which sphericity represents. Nevertheless, the sphericity affords a good first approximation to relative behavior during transportation, as shown by the correlation-coefficients of -0.79 and 0.71 mentioned in connection with Figure 3. The correlation-coefficient between sphericity and the writer's form-coefficient is 0.78, which also indicates a first-order agreement between the two.

The close correlation between the form-coefficient and flume-behavior, combined with the fact that it is a single shape-index, in contrast to the two of WADELL, suggests that the form-coefficient may prove useful in further experimental and analytical studies of particle-transportation. It is equally applicable to geological studies of the type in which sphericity is now applied.

Summary

Dynamic concepts are more significant than geometrical concepts in evaluating the effect of shape on particle-transportation. As illustrated by WADELL'S sphericity and roundness, various dynamic factors may be evaluated from the geometry of shape. The present experimental data suggest that although sphericity affords a first approximation to the dynamic behavior of particles, it is likely that some additional shape-factor may be present which will account for certain discrepancies in the relative behavior of particles of equal sphericity but different geometrical form. It was shown that an overall index of shape, here called the "form-coefficient," could be derived from settling-velocities by means of WADELL'S introduction of the nominal diameter into the coefficient of resistance. The form-coefficient is applicable both to the study of particle-behavior in flumes and to the geological interpretation of sedimentary deposits.

The writer is indebted to the John Simon Guggenheim Memorial Foundation for a Fellowship which made this study possible. The work was carried on at the Iowa Institute of Hydraulic Research, Iowa City, Iowa. The helpful suggestions and criticisms of Professors E. W. LANE and HUNTER ROUSE of that Institute are gratefully acknowledged.

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DISCUSSION

A. A. KALINSKE (University of Iowa, Iowa City, Iowa; communicated)--The careful and systematic experiments on the effect of shape on particle-movement in water-channels, as reported, form a most valuable contribution to our knowledge on sediment-transportation. The author is to be complimented on the thoroughness of his experimental work. The writer, however, does not

agree with some of the analyses made and the resulting framework into which the data are fitted. First, and probably most important, the FROUDE number of the channel-flow has no physical significance in regard to movement of particles on the bed. The author plots (v/V) and other quantities against F when in reality he is plotting only against V since the depth, y, was not varied. It should be noted that it is physically possible to keep V constant and vary F by changing y. Since it is only the velocity or drag on the bottom that influences particle-movement, the location of the free water-surface is immaterial. In fact, the experiments could just as well be performed in a closed conduit, in which case F has no meaning, and if the work is fundamentally sound the same results should be obtained.

Physically significant parameters could be obtained by the author's dimensional analysis if it were augmented by an analysis of the mechanics of the problem. Thus, since it is the bottom-velocity or shear which basically controls the particle-movement, the depth of flow is of no significance (unless, of course, the particles are so large that they occupy a large portion of the depth so as to restrict the flow or produce surface-waves). The significant Pi terms should then be: $(V/\sqrt{gd})$, (Vd/ν), (v/V), (ρ_2/ρ_1), and P. The first of these can be considered as a FROUDE number of the particle and the second the REYNOLDS number of the particle. It probably is more significant to use the ratio (ρ'/ρ_1), where $\rho' = (\rho_2 - \rho_1)$. In the author's equation (2) the REYNOLDS number of the particle can be omitted since the particles are quite large. Therefore, the plotting of Figure 2 should be (v/V) versus F of the particle. Of course, since the author did not vary d, the plotting would be similar to the present Figure 2.

Physical analysis indicates that the velocity of particle-movement, v, should be equal, or at least proportional, to $(v' - v_c)$, where v' is the velocity of the fluid acting on the particle and v_c the critical velocity for that particle. Therefore, let

$$v = b(v' - v_c) \tag{1}$$

where b is a proportionality-constant, probably very close to unity. The author's velocity, V, is the mean flow-velocity; of course, v' should be proportional to V for any particular test setup. Fundamentally, it would be better to measure v', and then the shape of the channel in which the tests are made will not enter the problem. In any case, if we assume v' and v_c proportional to V and V_c, respectively, we have the relation

$$v/V = b'(1 - V_c/V) \tag{2}$$

For any particle V_c is a constant so we have an equation which states that (v/V) is a hyperbolic function of V. Of course, for the author's data in Figure 2, V is proportional to his value of F.

Analysis of the author's curves in Figure 2 shows that the above equation (2) fits quite well, and the value of b' is between 0.9 and 1.0 for all the curves. Note that V_c can be evaluated from the data in Figure 2 using equation (2), and this would be the value when v = 0. The author's value of V_c, or critical FROUDE number, is not actually the value when v = 0, according to the author's statement.

It is of interest to point out that v_c can be expressed as $K\sqrt{\rho' dg/\rho_1}$ where K is a constant depending on the particle-shape. Putting this in for v_c in equation (2) above, we note that (v/V) is then really a function of (ρ'/ρ_1), $(V/\sqrt{gd})$, and a shape-factor. This verifies the writer's previous statement regarding (v/V).

The author's data regarding settling-velocity is most enlightening, and will permit simplification of sediment-movement analyses.

THE USE OF SAND-BEDS FOR COMPARING RELATIVE STILLING-BASIN PERFORMANCE

Fred W. Blaisdell

The erection of an engineering structure in a natural stream-channel usually introduces a problem in energy-dissipation, particularly in the case of high dams and steep flumes. The permanency of the structure, especially those located on loose, unstable soils, may depend entirely on how satisfactorily this energy can be dissipated.

The economical design of a stilling-basin by mathematical means to adequately dissipate the

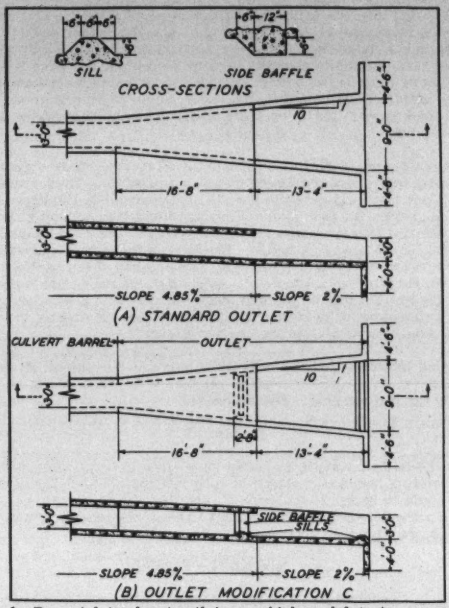


Fig. 1--Drop-inlet culvert outlets on which model-tests were made

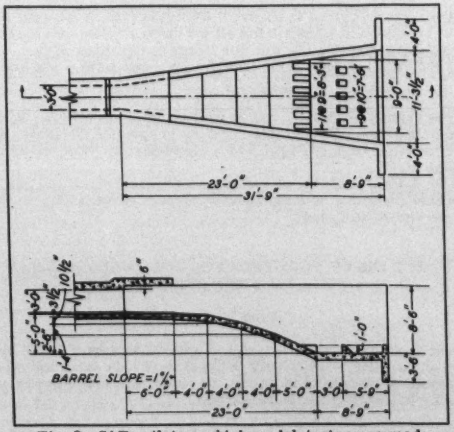
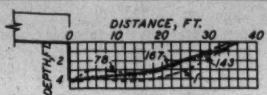
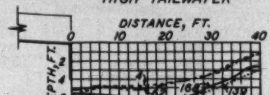


Fig. 2--SAF outlet on which model-tests were made



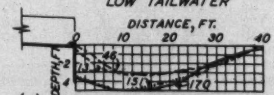
(A) STANDARD OUTLET, 30-MINUTE RUN, HIGH TAILWATER

Run	Model*	Q, cfs	Tail-water, ft
1	Full	271	3±
78	Full	267	3.47
143	Half	272	3.26
167	Half	254	3.07



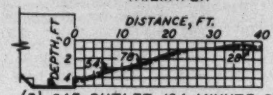
(B) STANDARD OUTLET, 30-MINUTE RUN, LOW TAILWATER

4	Full	259	1.42
62	Full	275	1.38
139	Half	278	1.01
168	Half	256	1.03



(C) C OUTLET, 30-MINUTE RUN, LOW TAILWATER

13	Full	269	1.42
46	Full	270	1.55
151	Half	274	1.18
170	Half	261	1.13



(D) SAF OUTLET, 104-MINUTE RUN

28A	Half	275	1.1
54B	Half	274	1.1
78B*	Full	267	1.3

A, stilling basin is rectangular in shape
B, stilling-basin side-walls diverge

*Scale-ratio is 1:12 for all runs except SAF-outlet run 78 which is 1:4.

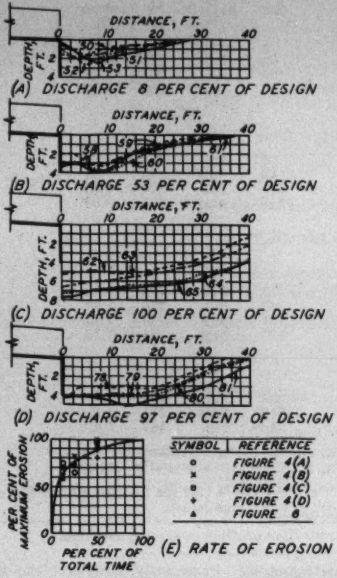
Fig. 3--Drop-inlet culvert outlets, center-line profiles of eroded sand-bed

energy below such a structure is very difficult if not impossible. Fortunately, many problems of this type can be solved by means of models, and this method has been used extensively in the development of designs for relatively large structures. When using models for the study of energy-dissipation it is desirable to maintain both geometric and dynamic similarity. However, since complete similarity depends on both the characteristics of the fluid and the material used for the stream-channel, it is not practicable to fulfill this requirement exactly.

The erosion in the stream-bed was used to compare the efficiencies of different types of stilling-basins in a model-study made by the United States Soil Conservation Service at the St. Anthony Falls Hydraulic Laboratory. No special effort was made to simulate the prototype bed-material, and in this respect complete similarity between the prototype and its model was not attained. Much interesting information has been gleaned from an examination of the data obtained from these tests and this information is presented here in an effort to show how much reliance can be placed in this type of model-study.

The models--The data presented here are abstracted from the results of tests made on six different models of culvert-outlets. These six models represented three different designs of outlets for use in connection with drop-inlet culverts. Although it is unnecessary to select any particular size of culvert as the prototype, a culvert three feet square was selected for the outlet-tests in order to have definite dimensions with which to work; the outlet-dimensions for other culvert-sizes can be obtained from the tests on these outlets by using the principles of geometric similitude.

The first tests were made on a one-twelfth-size model of a "standard" culvert-outlet (Fig. 1-A) based on the designs of NEAL MINSHALL [see 1 of "References" at end of paper]. Another series of tests was made on a modification of this model which has been designated the "C" outlet (Fig. 1-B). These two models were subsequently split along their vertical center lines and one-half of the model pressed against the side of a glass-walled channel, so that the scouring action under the nappe could be better observed. A comparison of the results obtained on the "full" and "half" models will be given presently.



Run	Length of run, min	Q, cfs	Tail-water, ft	Per cent of Max. erosion	Per cent of Total time
50	30	23	0.85	74	12.5
51	60	23	0.85	65	25
52	120	23	0.85	97	50
53	240	23	0.85	100	100
58	30	145	1.21	70	12.5
59	60	145	1.21	83	25
60	120	145	1.21	100	50
61	240	145	1.21	100	100
62	30	275	1.38	58	12.5
63	60	275	1.38	72	25
64	120	275	1.38	92	50
65	240	275	1.38	100	100
78	30	267	3.47	63	12.5
79	60	267	3.47	75	25
80	120	267	3.47	80	50
81	240	267	3.47	100	100

Note: Scale-ratio is 1:12 for all runs.

Fig. 4--Drop-inlet culvert outlets, center-line profiles of eroded sand-bed, effect of length of run

As the studies progressed a more efficient outlet was developed, the studies being made on one-twelfth-size half-models. This outlet (Fig. 2) is designated the SAF outlet or stilling-basin design. It is based on the rectangular stilling-basin apparently developed by the Bureau of Reclamation and described by WARNOCK [2], although the dimensions were modified somewhat. Subsequently, a one-fourth-size full-model of this same outlet was constructed and tested.

Limits of experimental precision--Before comparing quantitatively the results of changes in an outlet-structure, it is desirable to know the precision that can be expected from the experimental work. Otherwise, variations in the results which should be attributed to the test-methods might be attributed to the effect of changes in the outlet.

In Figure 3 there are presented center-line profiles of the stream-bed downstream from the three different types of outlets tested. These profiles were obtained from runs intended to be identical, except as noted. The runs were made several days apart, and at least 20 runs were made between each run intended to be identical. Consequently, the experiments should demonstrate the variations that may be expected in the scour-pattern for the same structure under the same test-conditions. It can be seen that the center-line profiles plotted for identical runs almost coincide, the vertical difference being generally less than 0.5 foot (0.5 inch in the model). Although there are occasional differences of about one foot, they are confined to scattered runs.

Apparently, any vertical differences between profiles greater than one foot may be assigned to changes in the outlet-structure, whereas vertical differences less than one foot may be due to experimental variations.

Length of run--It is, of course, desirable that the individual runs be made as short as pos-

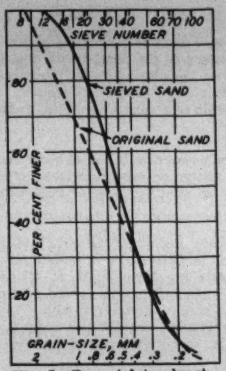


Fig. 5--Drop-inlet culvert outlets, mechanical analysis of sand used in tests

sible in order to expedite the work. On the other hand, they must be long enough to permit the scour to approach the maximum in order that the tests may be compared more accurately.

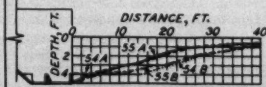
Center-line profiles showing the results of several tests made at elapsed times ranging from 30 min to 4 hr (8 min 39 sec to 1 hr 9 min 15 sec in the model) are presented in Figure 4. Similar information can be obtained from Figure 6. It will be noted that about 65 per cent of the total erosion occurred in 12-1/2 per cent of the total time and that the remaining 35 per cent of the total erosion took 87-1/2 per cent of the total time.

The increase in depth and volume of erosion with time is very rapid at first and then slowly approaches its maximum. This is clearly shown in Figure 4-E where the percentage of the total eroded area at the center-line and percentage-time are plotted. REHBOCK shows similar results [3].

The length of time used in the model-tests of the "standard" and "C" outlets was 8 min 39 sec. A 30-min length of run was used for the one-twelfth-size model of the SAF outlet and a 52-min length of run for the one-fourth-size model of the same outlet. These lengths of run were quite satisfactory in providing erosion-patterns that could be used to measure the relative efficiencies of the various outlets and modifications of them.

Size of sand--Two consecutive tests were made on a model of the SAF outlet; one using concrete sand and a second using the same sand in which the particles coarser than 12 mesh were removed. The mechanical analysis for these two bed-materials is shown in Figure 5. The results of these experiments are presented here for whatever value they may have, although the sands are not enough different to permit definite conclusions to be drawn.

The test-results are presented in Figure 6 for two lengths of run in the model, 30 min and 120 min (104 min and 415 min for the prototype). The center-line profiles of the eroded sand-beds were identical for each of the two lengths of run except near the end of the outlet. This difference is due to a localized eddy that was strong enough to carry away the fine sand but which had insufficient strength to remove the coarser material found in the original sand.



Run	Length of run, min	Q, cfs	Tail-water, ft	Per cent of Max. erosion	Per cent of Total time	Sand
54A	104	274	1.08	73	25	Original
54B	415	274	1.08	100	100	Original
55A	104	277	1.09	74	25	Sieved
55B	415	277	1.09	100	100	Sieved

Note: Scale-ratio is 1:12.

Fig. 6--Drop-inlet culvert outlets, center-line profiles of eroded sand-bed, effect of sand-size and length of run

It is apparent that there is little or no difference in the depths of erosion for the two sands used in these experiments. This was also found to be the case by REHBOCK [3] and by INGLIS, THOMAS, and JOGLEKAR [4] as regards the ultimate depth of erosion around bridge-piers.

Comparison of results obtained from full- and half-model tests--It was felt that it would be highly desirable to make a series of tests on the half-model, duplicating tests on the full-model, to determine what, if any, differences in the erosion-patterns could be attributed to the substitution of a glass plate for one-half of the model. Some boundary-effect was expected, and it was in an attempt to evaluate this and other effects that these tests were made.

In Figure 3-A the comparison of full- and half-model-test results is satisfactory, whereas in Figures 3-B and 3-C the comparisons are not as good. The comparison is satisfactory in Figure 3-D, but here there is also a difference in the model-sizes. It is not possible to state definitely that the poor comparisons shown in Figures 3-B and 3-C are due to the type of model, since the depth of tailwater for the half-model is about one-third less than the depth of tailwater for the full-model. The differences may be and very likely are due to the large differences in the depth

of the tailwater.

These tests show that the comparison between full- and half-model tests is satisfactory for high tailwater. It is not possible to reach a definite conclusion in regard to the comparison when the depth of tailwater is low. It should be kept in mind, however, when comparing the efficiencies of various outlets, that either the full- or the half-model tests should give equally good results; it is in a comparison between types of model rather than duplicate tests of a single model of each type that the comparison possibly becomes invalid.

Effect of model-size--The question, "Are the model-results truly representative of what may be expected in the prototype?" always arises in the mind of anyone analyzing model-experiments. The results of the immediately available tests are presented here in an effort to answer this question.

A full-scale model of a 2-foot by 2-foot standard drop-inlet culvert, including the outlet, was constructed by the Soil Conservation Service near Nelson, Wisconsin, in 1936 and was tested on April 8, 1937. Photographs, drawings, and a report on these tests were furnished by M. M. CULP. For a period of about 20 minutes the discharge was approximately 94 cfs and in this period a scour-hole about four feet deep was eroded near the end of the apron. This may be compared with model-run 78 (Fig. 4-D) where the corresponding discharge of the prototype was 267 cfs and a scour-hole having a maximum depth of five feet was eroded in 30 min. A comparison of the two models, adjusted for size, is presented in Table 1.

Table 1--Comparison of field- and laboratory tests on standard culvert outlets

Model	Discharge, cfs	Length of run, minutes	Scour-hole depth, feet
Full-scale model of 2-foot by 2-foot drop-inlet culvert	94	20	4.0
One-twelfth-scale model of 3-foot by 3-foot drop-inlet culvert scaled up to give results for 2 foot by 2-foot culvert (quantities are in terms of prototype)	97	24	3.3

A one-fourth-scale model was constructed full width and similar to the one-twelfth-scale half-model of the SAF outlet to determine the effect of model-size. The results of tests on the two sizes of model are presented in Figure 3-D. The same sand was used in each model, and, although the higher actual velocities in the large model caused more of the fines to be washed away, the results are nearly identical.

Since the same sand was used for the two different size models, these data also indicate that the size of the sand, within reason, is not a particularly important factor to be considered in making comparative measurements of this type.

Discussion of results--It has been shown here that comparative tests of the efficiencies of outlets are, within certain limits at least, apparently independent of the size of the bed-materials and model-scale. The laboratory observations of the half-models indicated that the eddies which caused most of the erosion had well-defined limits. These eddies were, nevertheless, strong enough to pick up and transport the bed-materials readily. The erosion, therefore, took place rapidly until the scour-hole boundaries were approximately coincident with the outer limits of the eddies causing the scour, after which the rate of erosion became very low by comparison. These are the reasons why the material to be used for the model stream-bed need not be exactly similar to the prototype bed-material in order that results may be obtained that are indicative of the prototype-condition. The same factors also explain why runs as short as 8 min 39 sec in the model produced erosion-patterns that were entirely satisfactory in making comparisons of relative outlet-efficiencies, and why such close agreement of the erosion-patterns was obtained for duplicate runs.

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DISCUSSION

ARNO T. LENZ (University of Wisconsin, Madison, Wisconsin; communicated)--Mr. BLAISDELL is to be commended for presenting, in a very orderly fashion, data showing the effect of certain test-variables on the results of model-tests. Unfortunately engineers are often required to make the assumption that a particular variable has no effect. At such times it is indeed comforting to know that others have found by actual test that such an assumption is based on fact.

It is to be feared, however, that the author is too modest in his comparison of full and half-model tests. Examination of Figure 3-A shows that the scour at a point 15 feet from the end of the apron in runs 78, 143, and 167 was 3.3 feet at the time the tailwater-level was about 3.26 feet. In Figure 3-B the scour of 5.0 feet in runs 4 and 62 with a tailwater-level of 1.40 feet confirms the well-known fact that low tailwater tends to increase scour. If it be assumed that the scour is in direct proportion to the lowering of tailwater-level, the further lowering to 1.02 feet in runs 139 and 168 should produce scour of 5.35 feet which is within one foot of that determined experimentally. Since scour tends to be accelerated at the lower tailwater-levels, the scour which might be estimated due to tailwater-level 1.02 would check within less than one foot that actually measured, indicating good agreement between the full and half-model tests. The difference in scour in runs 1 and 78 (Fig. 3-A) might be due to change in tailwater-level, and the same may be true for the curves shown in Figure 3-C, beyond ten feet from the apron.

The difference in scour-pattern close to the apron in Figure 3-C is of greater concern, however. It is often exceedingly important to know whether or not such scour will take place. If half-model tests showed scour where none was likely to occur in full-model tests an erroneous comparison might be made. Was there any indication in the half-model tests that the scour close to the apron was due to the boundary-effect along the glass wall? It has been noted in tests made by the writer at the University of Wisconsin that sand-profiles along the wall of the flume often are not representative of conditions at other points. Profiles are rarely taken closer than six inches from the wall. Since Figure 3-C is along the center-line and that center-line is at the glass wall it is just possible that the erosion-pattern some distance away from the glass wall would show closer agreement between the full and half-model tests.

In conclusion the writer again wishes to commend the author on a worth-while contribution to the practical phases of model-testing. The statement "The differences (between full- and half-model tests) may be, and very likely are, due to the large differences in the depth of the tailwater", deserves special emphasis, particularly to hydrologists, many of them field-men who are responsible for the collection of flood-discharge and elevation data. That such data are of great importance to the designing and testing engineers is evidenced by comparison of Figures 3-A and 3-B.

CRITERIA FOR DETERMINING SAND-TRANSPORT BY SURFACE-CREEP AND SALTATION

A. A. Kalinske

One of the most important problems relating to sand-movement by wind or water is the determination of the conditions for initial movement. Experimenters have recognized what appear to be three distinct methods of sand-and-silt movement by fluids: Surface-creep (called bed-load movement in hydraulics literature); saltation; and suspension. These three classifications seem to be fundamentally sound since each type of movement is controlled by a different set of forces acting on the sand-particles.

When the fluid-drag on a particle overcomes the gravity-forces (considering cohesionless material), the particle is displaced and rolls along with the fluid. As the drag is increased some of the grains may have exerted on them lifting forces and thus may get up into the faster-moving fluid. If, after getting into the moving fluid it attains sufficient kinetic energy, a grain on dropping

down (considering for the moment no turbulence) will impart some of this energy to another grain, knocking it off the bed, or perhaps it itself will bounce up. Thus grains may be carried along in a region near the bottom in the fluid at a speed corresponding to the moving fluid, without the presence necessarily of any turbulence. Such transport of sand is called saltation and has been quite thoroughly studied by BAGNOLD [see 1 of "References" at end of paper], both in the field and laboratory.

If turbulence is present, so that there exist upward velocity-components greater than the velocity of fall of the particles being considered, then transportation by suspension occurs. The criteria for transportation of material by suspension has been discussed in a previous paper by LANE and KALINSKE [2].

(A) Criterion for initiation of movement of sand-particles--Since it is the pressure- and drag-forces exerted on the individual grains which start movement, the problem fundamentally resolves itself into a study of the hydrodynamics of sand-grains. Most experimental studies to date have been concerned only with average conditions--that is, with average critical tractive force and average critical velocity. This does not seem to be fundamentally sound since it appears that the variations in local shear due to turbulence are of tremendous significance in the starting and maintaining of sand-movement. RUBEY [3], SHIELDS [4], and more recently WHITE [5] have analyzed the forces acting on individual grains, and WHITE has conducted some fundamental experiments. Considering a sand-grain resting on other grains, before it will be moved the force acting on it must exceed the value

$$f_g = \alpha \tan \phi \, \rho' \, g \, d^3 \qquad (1)$$

where $\rho' = (\rho_s - \rho)$, and ρ_s and ρ are the densities of the sand and fluid, respectively, g is acceleration of gravity, d is the particle-diameter, ϕ is the angle of repose of the grains, and α is a constant dependent on the type of flow around the grain. At low REYNOLDS numbers the force acting on the grain is predominatingly tangential and at higher values the fluid-force is predominatingly normal. This results in a vertical shift of the resultant line of action of the fluid-force on the grain.

Considering uniform sand, if the number of grains per unit-area which is effective in taking the fluid-drag is equal to (n/d^2) then the drag per unit-area τ_o is equal to $(f_g n/d^2)$. The value of n depends on the closeness of packing of the grains and can be evaluated by counting the grains which are lying on the top of the sand. If the sand is non-uniform in size then an estimate must be made of the proportion of the total drag taken by the sand-grains of the size being considered. The critical drag-force per unit-area is then

$$\tau_c = \alpha n \tan \phi \, \rho' \, g \, d \qquad (2)$$

When the value of $R = (U^* d/\nu)$, where $U^* = \sqrt{\tau_o/\rho}$ and ν is the kinematic viscosity, is less than about 3.5, WHITE'S experiments indicate that α is about 0.20. When this parameter is larger than 3.5 the individual grains begin to shed small eddies which tend to produce a fluctuation in the force acting on the grains. This occurs even though the main stream may be non-turbulent. Thus the critical value of bottom-shear will depend on whether the so-called "REYNOLDS number", R, of the grain is larger or less than 3.5. Experiments for determining τ_o for various materials and conditions can probably be best made in contracting water-tunnels where sufficient shear can be developed without the creation of large-scale turbulence in the main stream. The use of viscous liquids other than water may also be desirable. For values of R greater than 3.5 WHITE found the values of α were about 0.25.

In any case it is apparent that the critical value of unit-shear required to move sand-particles can be experimentally determined; the problem now remains as to how this value of τ_c is to be used in natural water-courses. First, the important item to keep in mind is that, if even momentarily the value of τ_c is exceeded, movement will result. In normal open channel-flow the turbulence present will cause the shear to fluctuate considerably. This fluctuation will undoubtedly be related to the velocity-fluctuations. Experimental evidence indicates that the velocity-fluctuations are distributed according to the normal-error law. Thus the standard deviation of the horizontal velocity, $\sigma = \sqrt{(U - \bar{U})^2}$ completely describes the fluctuation. It can be shown that values of $(U - \bar{U})$ equal to 3σ will occur only on the average about 0.3 per cent of the time. Therefore, for practical purposes we can assume that the maximum value of $(U - \bar{U})$ will be 3σ. Very few measurements of σ near boundaries are available; however, there are data that indicate that $(\sigma/\bar{U})$, where $\bar{U}$ is the mean velocity at the point considered, may be of the order of 1/3. In that case

$U_{max} = 2\,\overline{U}$ approximately, and if the drag on a particle varies as the square of the velocity it is apparent that we must expect momentary values of drag equal to four times the mean value calculated from surface-slope and depth of water-flow. In fact, it is possible for the local mean drag to be zero, yet sand-movement can take place due to the turbulence fluctuations with the resultant momentary high drag-forces.

It thus appears that experiments on bed-sediment movement in laboratory or natural channels involving the measurement of average velocity and drag cannot give fundamental data. Rather, what is necessary is the determination of values of σ and an evaluation from such measurements of how and to what degree the shear fluctuates. If τ_c is known for any sand, then whether movement takes place or not depends on whether from a statistical standpoint in the practical case being considered, the value of τ exceeds τ_c for any significant portion of the time. The mean value of the shear may be of no direct significance.

(B) Regarding total bed-load transport--No attempt will be made to develop a complete and final formula for the rate of bed-load movement, since existing data are not of the type that can be used to evaluate the constants in any such equation. Only the general form of what is believed to be the correct type of equation will be presented. Considering any single particle, the velocity at which it will move, U_g, at any instant will be equal to $b(U - U_c)$ where U is the fluid-velocity acting on the grain and U_c the velocity associated with the critical tractive force τ_c, and b is a numerical constant. If the number of grains per unit-area of the size being considered is (n/d^2) then the rate of transportation per unit-time per unit-width of bed is

$$G = U_g \rho_s g n d \tag{3}$$

However, the value of U_g varies with time, since U fluctuates, and therefore it is necessary to evaluate its average value. Experiments indicate that the velocity in turbulent flow fluctuates according to the normal-error law, so that the frequency-function of U is

$$f(U) = (1/\sqrt{2\pi}\,\sigma)\, e^{-(U-\overline{U})^2/2\sigma^2} \tag{4}$$

where $\sigma = \sqrt{\overline{(U - \overline{U})^2}}$ and $\overline{U}$ is the mean fluid-velocity at the sand-grain level.

The mean value of $\overline{U}_g$ will then be

$$\overline{U}_g = b\int_{U_c}^{\infty} (U - U_c)\, f(U)\, d\,U \tag{5}$$

Let $[(U - \overline{U})/\sigma] = t$, and $t_c = [(U_c - \overline{U})/\sigma]$. We then have

$$\overline{U}_g = b(\sigma/\sqrt{2\pi})\int_{t_c}^{\infty} te^{-t^2/2}\, dt + b(\overline{U} - U_c)\int_{t_c}^{\infty} (e^{-t^2/2}/\sqrt{2\pi})\, dt \tag{6}$$

$$= b(e^{-t_c^2/2})/\sqrt{2\pi} + b(\overline{U} - U_c)\, f'(t_c) \tag{7}$$

Where $f'(t_c)$ can be found from tables in books on statistics. Note that the value of $\overline{U}_g$ depends on σ, $\overline{U}$, and U_c, and that $\overline{U}_g$ may have a positive value even though U_c is greater than $\overline{U}$.

Where the entire drag is due to the bed then the value of (σ/U) tends to be quite constant and certain data on hand indicate that this ratio may be of the order of 1/3. If such is the case then the value of $\overline{U}_g$ as given by equation (7) depends only on U_c and $\overline{U}$; the latter is of course dependent on the grain-size and the bottom-shear τ_o, and would be evaluated from the velocity-distribution expression for flow over rough surfaces.

Perhaps there are data in existence which would permit a checking of equation (3); however, the writer has not, as yet, had an opportunity to make a thorough investigation. The physical basis for equation (3) appears fundamentally sound since it reduces the problem of bed-load movement to the evaluation of a critical drag or velocity under controlled laboratory conditions, and an evaluation of the turbulence under various natural conditions.

(C) Criterion for saltation--As soon as the movement of sand has been initiated some of the particles may get lifted off the bed into the fluid-stream. It can be assumed that they may thus

acquire a velocity equal to that of the fluid. An analysis will be made to determine the maximum height that a sand-particle moving at a specified velocity will bounce under perfect conditions when striking the bed. It will be assumed the particle has acquired kinetic energy equal to $(k\ \rho_s\ U^2\ d^3/2)$ and that it will strike a surface such as to cause it to have all its velocity directed straight upwards. The height of vertical rise will be rd.

The original kinetic energy will be used in raising the particle against gravity and overcoming fluid-friction as its velocity changes from U to 0. The work done against gravity will be $k\ r\ \rho'\ g\ d^4$. The work done by the fluid-resistance in the vertical direction will be equal to the average resistance times rd. The fluid-resistance is

$$R = C\ A\ \rho\ U^2/2 \tag{8}$$

where C is a drag-coefficient and A the projected area. Let the average resistance be expressed thus:

$$R_{ave} = (m\ C\ A\ \rho\ U^2/2) \tag{9}$$

where m is the ratio between the average resistance and its initial value associated with the initial velocity U. The work done against this resistance will be (R_{ave} rd). On equating the initial kinetic energy to the total work done we have

$$(k\ \rho_s\ U^2\ d^3/2) = [rkd^4\ \rho'\ g + (m\ Crd\ A\ \rho\ U^2/2)] \tag{10}$$

$$r = [0.5k\ \rho_s\ U^2\ d^3/(gkd^4\ \rho' + 0.5mCd\ A\ \rho\ U^2)] \tag{11}$$

Assume that the sand-particle approximates a sphere and that the average fluid-resistance can be expressed sufficiently accurate by assuming a linear change in U^2 thus making m = 1/2. We then have

$$r = \left\{1/[(2gd\ \rho'/\rho_s\ U^2) + 0.75\ C\ \rho/\rho_s]\right\} \tag{12}$$

Note that the value of r increases with the velocity and decreases with the ratio (ρ/ρ_s). In order to compare the value of r for similar conditions for air and water the value of U should be expressed so the shear is identical. BAGNOLD in his studies of saltation developed an expression for the critical velocity at which sand-movement started thus

$$U_c = 5.75\ M\ \sqrt{\rho' gd/\rho}\ \log\ (30y/e) \tag{13}$$

where M is an empirical coefficient, e is the height of the surface-roughness, and U_c is the velocity at a vertical distance y which causes sand to just begin to move. If the surface-roughness is caused just by the sand-grains then e = d and U_c could be calculated for y = e. However, for the time being, substitute the value of U_c as given by equation (13) for U in equation (12). The value of r then becomes

$$r = (\rho_s/\rho)/(B + 0.75C) \tag{14}$$

where $B = [0.06/M^2\ \log^2(30\ y/e)]$. (BAGNOLD'S value for M was about 0.10.) Thus for conditions of the same value of shear the value of r depends on the ratio (ρ_s/ρ), and therefore, for the same size of particle the height of bounce in water will be only about 1/800 of what it is in air. This apparently indicates that saltation will be many times more significant in air than in water. In fact it does not appear possible even at high water-velocities for sand-particles to bounce up in the saltation-phenomena more than a few grain-diameters. It may thus be concluded that in water-streams, when the velocity reaches sufficient magnitudes to cause saltation, the turbulence will be such as to place the material in suspension and thus entirely obscure any saltation-effect.

(D) Summary--An expression for the critical tractive force necessary to initiate sand-movement is presented, and how this tractive force can be determined under controlled laboratory conditions in non-turbulent fluid-streams is indicated. Knowledge of this critical tractive force and the mean velocity associated with it, and of the magnitude of the velocity-fluctuations near the bed of natural streams, permit a determination of when sand-movement will take place in nature.

The instantaneous rate of sand-grain movement depends on the difference between the fluid-velocity at the instant and the critical velocity. The evaluation of the mean value of this velocity-difference, assuming the normal error law for the fluid velocity-fluctuations, is the significant

item in the bed-load expression developed in this paper. The physical basis behind this bed-load equation is the critical drag or velocity and the intensity of the velocity-fluctuation.

Since bed-load or surface-creep has been observed to be associated with saltation, especially in the movement of sand by wind, an analysis is made of the criterion for saltation by developing an expression for the maximum height of sand-particle "bounce" in terms of the grain-diameter. This expression indicates that this height of bounce is directly proportional to the ratio of sand-density to fluid-density. Therefore, for equal drag, this height of grain-rise in the saltation-phenomena in water will be of the order of 1/1000 of that in air, or for most practical conditions, a few grain-diameters.

Acknowledgment--The writer wishes to thank Professor E. W. LANE for originally presenting to the writer certain of the basic ideas on which this paper is based.

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DISCUSSION

HANS ALBERT EINSTEIN (Soil Conservation Service, Greenville, South Carolina)--Mr. KALINSKE tries to reconcile the main ideas of the writer's recent article on bed-load movement [Formulas for the transportation of bed load, Proc. Amer. Soc. Civ. Eng., v. 37, No. 3, pp. 351-367] with the notion of initial movement. Unfortunately, he could not find any measurements to support his formulas, which, therefore, are based only on a number of assumptions and the judgment of the author himself. A short review of those assumptions, however, seems necessary for the understanding of a later success or failure of the formula to describe bed-load movement.

The first assumption, "it appears that the variations in local shear due to turbulence are of tremendous significance in starting and maintaining of sand movement," is the main idea of the writer's original article [see above] and, therefore, is not new. The second assumption states that there is no direct relation between the average flow-conditions in a vertical and the local fluctuations of shear along the bed. Generally, this assumption is true. In the case of uniform flow on a granular bed, however, this relation exists, and can be used to advantage in formulating a law for bed-load transportation. Only flume-studies on a long sand-bed are able to show this relation. The third assumption introduces the normal-error law for the distribution of turbulence-velocities. In general this assumption is correct. For the immediate vicinity of the bed, however, caution seems advisable, since the turbulence is created there and may not have been able to develop its final structure. The writer's empirical determinations that are described in his article on bed-load movement give a slightly different law for this distribution. The formulas (4) to (7) stand or fall with this third assumption.

It is worth mentioning that the introduction of the normal-error law excludes automatically the existence of a well-defined point for initial movement. The author is forced, therefore, to define it at will. This fact makes initial movement theoretically unimportant.

While only future measurements will be able to prove the value of Mr. KALINSKE'S method of developing a bed-load formula, his chapter "Criterion for saltation" reveals and explains why saltation is unimportant as a way of transportation in water. The knowledge of this fact solves a number of problems and simplifies the description of bed-load transportation considerably. It explains, too, why the same bed-load formulas apparently cannot be used for transportation in water and in air.

THE HYDROLOGIC ASPECTS OF BEACH-MATERIAL SUPPLY, WITH SPECIFIC REFERENCE TO THE SHORELINE AT LONG BEACH, CALIFORNIA

Warren E. Darrow

Introduction

This paper attempts to throw additional light on the production, transportation and deposition, or continued transportation of debris, which in the form as it reaches the ocean shorelines, constitutes a large portion of the material by which our beaches are nourished and maintained.

The scarcity of data susceptible of correlation between the hydrological characteristics of river-basins which discharge at the shorelines of the United States, and the volume of material transported by the respective streams, does not permit thorough accomplishment of the desired result.

Of the class of rivers mentioned, the Los Angeles River System is probably outstanding in the result of investigation by several agencies thus far. For that reason, it is made the special subject of this study.

(I) Past history

(1) Precipitation in the area of southern California, during the Cretaceous, Tertiary, and Quaternary periods, doubtless played an important role in producing materials of erosion and in a manner quite similar to that at present.

In conjunction with the diastrophic movements of uplift and depression and with changes of sea-level, the agencies of weathering, erosion, transportation, and deposition of clastic sediments were active then as now.

(2) Geographical location of streams and the shoreline, of necessity and by the very activity of these agencies, must have changed. Authorities apparently agree that since the time of the Cretaceous period, general displacement of the southern California shoreline has tended in a westerly direction.

Specific movement, during the Pleistocene and Recent epochs, of that portion of the shoreline of San Pedro Bay which defines the seaward limit of the Los Angeles River Basin, may be said to have taken place in a southerly direction and for an average distance of 15 to 20 miles.

(3) Subsurface investigations in the area of the outwash plain above described indicate the total thickness of accumulated alluvium equal to a maximum of 2,000 feet in locations northeasterly from the city of Long Beach. Erosion, accentuated by torrential rains, in conjunction with crustal movements of depression in the plain and uplift in the adjacent hills, have produced such a deposit.

The lower channel of the Los Angeles River is located in this area.

(II) Topographic features of the river-basin

(4) Situated southerly from and receiving the impetus of flashy runoff from the San Gabriel Mountains, the river-basin is characterized by steep mountain slopes, valleys with their axes lying in an east-west direction, and a comparatively narrow coastal plain area which consists of a portion of an immense integrated debris-cone.

The San Gabriel Mountains within the basin, average 5,500 feet in elevation, with a maximum of 7,078 feet. Lesser ranges situated nearer the coast have elevations from 2,400 to 3,100 feet. The mountain areas rise generally at the rate of 2,000 feet per mile from valley-floors to the summits.

Experience indicates that these areas may be subject to burning about once every 20 years.

(5) Influx of population, due to extensive agricultural and commercial activity in recent years, has advanced the number of city inhabitants in the watershed to about 2,000,000.

(6) The Los Angeles River itself rises in the hills bordering the westerly portion of the San Fernando Valley. It then flows easterly a distance of 30 miles, turning southwesterly in the

proximity of Glendale and through the city of Los Angeles, and thence southerly for an additional length of approximately 20 miles to the northerly shoreline of San Pedro Bay. The main stream is about 50 miles in total length. The slopes, expressed in feet per mile over the longest water-course may be designated as 16, 34, and 230 feet, respectively, for the Coastal Plain, San Fernando Valley, and La Crescenta-Canada Valley. The drainage-basin covers a total area of 818 square miles of which 330 square miles consist of steep mountain slopes while the remaining area of 488 square miles is occupied by valleys, low foothills, and the comparatively narrow strip of coastal plain.

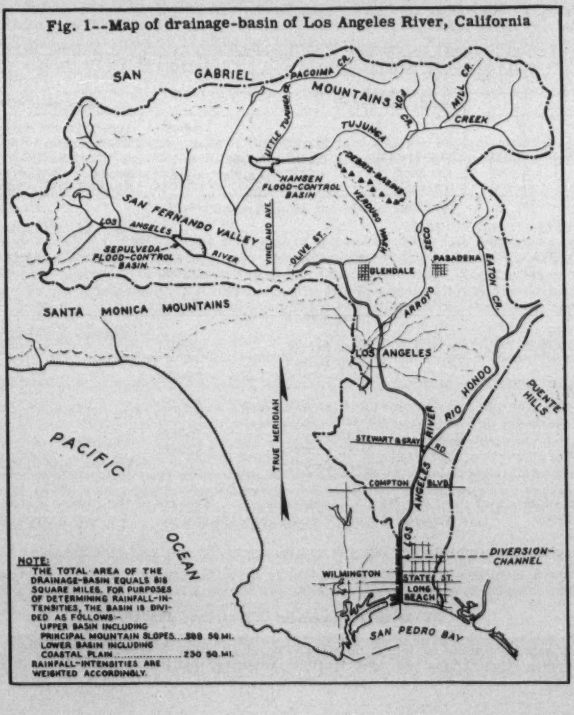
(7) Surface-cover is lacking over a considerable percentage of the slopes, this condition being emphasized especially at the time of burning over. Unconsolidated materials in large quantity are then subject to rapid erosion and transportation to the water courses.

(III) Rainfall-characteristics

(8) The major portion of seasonal rainfall over the basin occurs usually during one or two months of the winter season. The period from May to October, in fact, is designated as the dry season during which period there may be as many as 125 days, at some of the rainfall-stations, when no precipitation is recorded. The wet season extends from November to April.

Temperatures are in general mild. Humidities are low except during periods of torrential rains. The average annual sunshine is about 72 per cent of the maximum obtainable. Prevailing winds in the drainage-area are of light to moderate velocities from the west.

Fig. 1--Map of drainage-basin of Los Angeles River, California



(9) Cyclonic-wave disturbances arising on a polar front and normally situated in the vicinity of the Aleutian Islands, are the origin of the most torrential rains affecting the Los Angeles River Basin.

In the summertime, this front, after reaching the Continent, is located far to the north and the accompanying disturbances seldom travel south as far as the river-basin under discussion. During the dry season, however, heavy showers are produced in the mountains north of the Gulf of Lower California, by the movement of warm air from the Mexican interior.

(10) The polar front, on the other hand, moves further southward from September until April and the cyclonic-wave disturbances occasionally affect the basin. Rain in this area, however, may approach from the westerly quadrants included from southeast to northwest. Position of the air-mass type and the intensity of the disturbance determine the intensity of rainfall and the distribution thereof.

(11) Frequency of storms--Severe storms with rainfall from 4 to 24 days in duration over this portion of California have been recorded since December, 1862. Since that date and prior to the completion of the Los Angeles River Diversion-Channel at Long Beach in 1921-22, as many as 14 storms with marked intensity of precipitation have been noted. During this period, the natural point of discharge of the river was located in the drowned valley at Wilmington and in the rear of the shoreline of San Pedro Bay.

Subsequently seven storms of severe proportions are of record, although in varying detail. These are tabulated in the first column of Table 1 and as available data permitted, the maximum rate of discharge is given in the fifth column, for the corresponding storm-period.

Table 1--Approximate correlation of hydrological data of the Los Angeles River Basin with respect to material deposited at the shoreline of San Pedro Bay

Rainfall and runoff					Deposits at shoreline
Storm-period	Days of rain	Weighted average rainfall	Location of gaging-station	Maximum daily discharge	Approximate estimates, volume of deposits at shoreline since completion of by-pass diverting mouth of the river from the Los Angeles and Long Beach harbors
		inches		cfs	cu yd
Dec. 17-27, 1921	10	16.2	.....		1921-27, deposits not estimated
Apr. 1-8, 1926	7	....	.....		
Feb. 10-16, 1927[a]	5	....	Willow Street	51200	1927-36 estimated 5,000,000[b]
		....	Stewart and Grey Road	29400	
Dec. 30, 1933 - Jan. 1, 1934	3	10.8	State Street, Long Beach	37500	
Feb. 2-23, 1936	..	....	.....	.....	1936-38, 6,000,000[b]
Feb. 13-14, 1937	..	4.0	State Street, Long Beach	20500	
Feb. 27 - Mar. 3, 1938	5	14.1	Above Arroyo Seco	67000	
		....	Stewart and Grey Road[b]	63000	
		....	Ditto[c]	79000	
Mar. 2, 1938		....	State Street, Long Beach[d]	99000	1938-41, 9,000,000[d]

[a] Date of completion of the Long Beach Breakwater. [b] Reports of the United States Engineer Department. [c] Los Angeles County Flood Control District. [d] From Harbor Engineers Report.

Available data would indicate the deposits to average at the rate of 1,000,000 cubic yards annually.

(IV) Debris-movement in the river-channel

(12) No measurements of debris in suspension or in bed-loads have been made insofar as is known. Certain observations and investigations, however, made subsequent to the flood of March,

1938, in the river and tributaries, indicated in an approximate manner the magnitude of the partial or total load at various locations.

In the channel of the main stream between the confluences of Verdugo Wash and Arroyo Seco, where the paved levee-slopes remained essentially intact, there were removed approximately 3,000,000 cubic yards of material from the bed of the river for the purpose of restoration to the designed bottom grade.

(13) Investigation of the actual rate of transportation of sediments through the main river-channel for a distance of 36 miles, was originated approximately three years prior to the storm of 1938. A profile-survey and cross-sections were begun at that time, although portions of the work were delayed until just before the storm occurred. The survey extends from Vineland Avenue to the mouth of the river. Construction obviously obliterates the record in some areas, and affects the movement of sediment in other areas as well.

A computation of scour and fill from surveys thus made, will hardly provide an approximate measure of the material actually in transport. It is probable that on a rising stage, due to torrential runoff, considerable depths of material are removed by scour but record of the action is physically impossible during many of the flood-periods. Furthermore, on the succeeding falling stage, the scoured areas are subject to refill, and in many instances as found by survey, to a point above the elevation shown on the original cross-sections. Only the net section therefore, resulting from the flow due to the storm is obtainable.

(14) Probings at two sections separated by a distance of 200 feet were made in the diversion-channel at a location near the mouth of the river where the width measured 540 feet. By means of cross-sections plus the results of the probings, a scour of 30,800 cubic yards was indicated. Subsequently there was a deposit of 29,600 cubic yards of material. These observations cover the period from May 28, 1936, to May 11, 1938, and apparently the greater portion of this movement occurred during the notable runoff of February to March, 1938. Under the caption of "Deposits at shoreline," Table 1, it will be noted that an estimated discharge of 6,000,000 cubic yards of debris occurred in this period.

A comparable calculation of rates of flow of debris within the stream-channel apparently must await the development of further data, and then must be confined to a statement of capacities which exist during periods of flashy discharge.

(V) Deposition at the shoreline

(15) In the period of 1921-22, the diversion of the mouth of the Los Angeles to a direct connection with the shoreline, was completed. Thus the river-channel was by-passed around the low areas of natural discharge at Wilmington, the present site of the Los Angeles inner harbor. Wilmington Harbor was at that time representative of a drowned valley in the latter stages of alluviation from the debris discharged under natural conditions by the river-system.

(16) By virtue of this diversion, means is afforded for observation of the actual phases of the spasmodic transfer of a large amount of material from the river-basin to a new delta at the shoreline.

Confinement of the new channel to a comparatively narrow width of 600 feet within the area of the city of Long Beach permitted only that width at the intersection with the shoreline. River-discharge with its sediment-load is poured through this funnel beyond which the debris spread itself rather freely until the Long Beach Breakwater was completed in 1927. This structure is built in alignment with the west bank of the diversion-channel, for a distance of 4,200 feet, and then extends southwestward a further distance of 3,400 feet. The breakwater prevents westward extension of sediments in the delta and checks the natural littoral drift which formerly carried some of the material in an easterly direction along shore.

(17) Hydrographic surveys prior to the opening of the channel, together with periodic soundings obtained since, have provided a means of estimating volumes of sediment-discharge. Results of the estimates by several agencies are shown in the extension of Table 1, and total approximately 20,000,000 cubic yards for the period 1927-1941.

(18) Yield at the shoreline--Examination of Table 2, showing the action of debris basins of Los Angeles County, provides an approximate value of the rate of erosion per unit of area which is more especially applicable to the higher elevations of the watershed. The catchment of sedi-

ment by 16 dams during the storm of 1938 and its consequent runoff, amounted to a total of 642,500 cubic yards. The total basin-area concerned presents a total of 25-1/2 square miles. By simple computation, for the storm, the approximate volume of erosion per square mile in these areas is calculated at 25,200 cubic yards.

Table 2--Action of debris-basins in Los Angeles County, California, flood of March, 1938

Debris-basin	Drainage-area	Mean slope	Total capacity[a]	Burned area			Debris deposited flood, February-March, 1938	
				Year burned	Total area burned	Per cent area burned	Total	Rate of deposit
	sq mi	ft/ft	cu yd				cu yd	cu yd/sq mi
Brand	1.06	0.224	69,500	1927	0.77	72	13,000	12,250
Dunsmuir	0.83	0.235	128,200	1933	0.78	94	58,000	70,000
Eagle-Goss	0.63	0.155	71,900	1933	0.46	73	41,000	65,000
Fair Oaks	0.26	0.226	20,200	1935	0.26	100	11,900	45,700
Fern	0.30	0.229	21,100	1935	0.30	100	20,700	69,000
Haines	1.51	0.186	158,200	1933	1.01	67	54,500	36,000
Hall-Beckley	0.83	0.160	91,800	1933	0.63	76	86,100	104,000
Hay	0.17	0.244	37,800	1933	0.06	35	11,000	65,000
Las Flores	0.45	0.306	36,400	1935	0.31	69	37,500	83,300
				1922	0.14	31		
Lincoln	0.51	0.147	23,500	1935	0.50	99	17,000	33,400
Nichols	0.94	0.082	32,200	....	....	...	18,000	19,150
Pickens	1.89	0.158	112,700	1933	1.75	93	110,000	58,200
Shields	0.27	0.292	45,500	1933	0.24	89	34,950	129,000
Snover	0.24	0.243	34,800	1933	0.11	46	14,500	60,400
Sunset	....	0.304	.....	1927	0.42	100	.....	.....
West Ravine	0.24	0.195	44,900	1935	0.24	100	29,400	122,000
Verdugo	15.24	0.029	105,700	1933	4.55	30	85,000	5,600
				1927	1.78	12	.....	.....
Totals	25.47	.....	.....	....	....	...	642,550	.....

[a] The total capacities of debris-basins are taken from records of the Los Angeles County Flood Control District.

Note: These data abridged from reports on Flood Control by the United States Engineer Department, 1938.

Areas of lesser degree of slope and at lower elevations than those where the flow is checked by the debris-dams, may have exhibited different rates of erosion. However the evidence of prior years is rather conclusive in the great cones of the coastal outwash plain, of tremendous depositional activity. As a matter of fact, provision was made in the designs of a number of the debris-basins for erosional capacities of 100,000 cubic yards per square mile.

(19) In the absence of available data, presumably obtainable from an inspection of the entire drainage-basin, and considering the extent and distribution of the area represented by steeper slopes of the mountainous section of which there are 388 square miles, it appears reasonable to assume that in a single year, an average equal to 50 per cent of the total area of the basin may be subject to marked erosion from precipitation. In round numbers, the assumption is made that 400 square miles will be thus affected in the average year.

It will be further noted that a period of 14 years elapsed from the time of completion of the Long Beach Breakwater in 1927 to the limiting date of the estimate of 1941 of the volume of river-borne sediments deposited adjacent to and easterly from the breakwater.

In the event the above assumption in reference to erosional extent is approximately true, a relation between such eroded area in the river-basin and the volume of deposit at the shoreline, is shown by the computation ($20,000,000/400 \times 14$) = 3600 cubic yards, average annual deposit per square mile of the eroded territory.

(20) The foregoing estimated results of erosion and subsequent deposit at the shoreline indicate, for the Los Angeles River-Basin with its variable topographical features, surface-characteristics, and climate and as affected by torrential rainfall, that 15 to 25 per cent of the volume of the material eroded from the surfaces may be expected to reach the shoreline as a source of beach-nourishment.

Structures which change the course of natural flow of debris within the basin have a problematical effect when considered in conjunction with the numerous variables involved.

(21) Increase or decrease of debris in the Los Angeles Basin--Much is involved in the determination of actual rate of discharge, and whether there is a tendency for increasing or diminishing the volume of debris at the delta. Data susceptible of correlation and rational analysis are not plentiful.

That the sediment-load of the river has been materially reduced in recent years is apparently the opinion rather generally expressed. During the same period the number of flood and sediment control-structures have been substantially increased.

No major storms have occurred since completion of the Hansen and Sepulveda dams situated in the San Fernando Valley. Small debris-basins only were functioning at the time of the storm of 1938 shown in Table 1 as the last major disturbance. Interpretation as to total overall result of structures now completed in the watershed, will obviously depend upon future rainfall-intensities.

The debris- and retarding-basins tend to impound material from upstream, but on the other hand, the improved and leveed channels below tend to insure the transport of sediment passing through the basins, to the ocean shoreline.

Thus far, providing the correlation given in Table 1 is not in substantial error, the accumulations at the shoreline have apparently varied in proportion to the rainfall-intensities.

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DISCUSSION

CARL B. BROWN (Soil Conservation Service, Washington, D. C.)--Mr. DARROW'S paper has been of much interest to me, first, because he has had the fortitude to tackle a critical problem on which few useful data exist, and secondly, because I have worked intermittently for several years

on the problems of erosion and sedimentation in the Los Angeles Area in connection with investigations of the Sedimentation Division of the Soil Conservation Service.

The principal conclusion of Mr. DARROW'S paper is that the amount of material transported to the shoreline by the Los Angeles River in the 14 years from 1927 to 1941 varied approximately with the weighted average rainfall- and discharge-intensities. In a broad way this conclusion is probably true not only for the Los Angeles River, but for erosion and sediment-transportation generally, provided there is no change in the sediment-sources or sediment-supply. This latter qualification is the crux of the problem as it relates to Los Angeles beaches, for in the past three years large new flood-control reservoirs and channel-improvements have materially altered the potentials of sediment-supply in the drainage-basin of the Los Angeles River.

My study of deposition at the mouth of the Los Angeles River has led to substantially different figures from those presented by Mr. DARROW. The actual area covered by comparable surveys up to 1940 extends only 3,600 feet east from the Long Beach Breakwater, which is an extension of the west bank of the river, and from the mouth of the river near Ocean Drive to contour -30, some 3,000 to 4,000 feet off shore. For this area I have calculated the deposition between elevations + 15 and -30 as approximately 4,046,000 cubic yards from 1921 to 1927, approximately 736,000 cubic yards from 1927 to 1934, and approximately 5,600,000 cubic yards from 1934 to 1938 (after the flood of February 27 to March 2). These figures do not represent the total sediment-load of the river for these periods, as much material was transported farther seaward than contour -30, and prior to completion of the breakwater in 1929 unmeasured sediment was deposited west of the mapped area above contour -30. The total of Mr. DARROW'S figures, 20,000,000 cubic yards, which corresponds with an estimate contained in a recent report of the Long Beach Harbor Department, is perhaps not unreasonable for the total sediment brought to the ocean by the river since 1927. The interpretation that 9,000,000 cubic yards has been delivered since the storm of March, 1938, seems untenable, however, when one compares the relatively low discharges during the three years, 1938-41, with the flood-discharges of earlier years. Furthermore, the material transported beyond contour -30 is probably for the most part so fine-textured that it would not constitute an appreciable part of the beach-supply.

By comparing cross-sections of the Los Angeles River Channel from the ocean to Lakersham Boulevard and of the Rio Hondo up to its junction with the San Gabriel River, I have calculated that between the dates when the cross-sections were established, 1935-37, and a few months after the flood of March, 1938, when they were resurveyed, the net erosion from channels and banks amounted to approximately 6,474,000 cubic yards, or more than the deposition in the measured harbor-area. Some of this material eroded from the channel was deposited overbank, and doubtless a considerable part of it was transported beyond contour -30.

As the flood-control reservoirs and debris-basins built prior to 1938 held back most of the erosional debris originating in the mountains, the only other major sources of sediment were the minor channels, many of them cut by overflow from the major channels, and sheet- and gully-erosion below the mountain areas which was of rather minor importance with respect to its net contribution to the sediment-load of the river.

I would not question an estimate of 10 or 12 million cubic yards for the total sediment transported to the ocean by the Los Angeles River in March, 1938. At least half this load, however, must have been silt and clay, which does not contribute to the supply of beach-material. I interpret the available data, therefore, to indicate that a very large part of the material that would contribute to the beach-supply was derived from channel-erosion in the March 1938 flood.

What, now, will be the effect of constructing the Hansen and Sepulveda flood-control dams and of paving the channel-sides? As these developments are designed to hold flood-flows to channel-capacity and prevent bank-scour, it is obvious that if they are effective, the principal source of sediment-supply in the flood of 1938 will be eliminated. The great bulk of the sediment of grade-sizes that might contribute to the beaches will be deposited in the new flood-control reservoirs or the older reservoirs and debris-basins above them; channel-stabilization and controlled flow will eliminate stream-bank erosion in the major channels; and the soil-conservation program being developed in the area will reduce the contribution of material washed into the river from sloping lands. If the beds of the improved channels tend to be scoured, steps will doubtless be taken to stabilize them by sills or other means. Therefore, it would appear that the supply of beach-material is destined to be less in the future than it has been during the past decade or two.

WARREN E. DARROW (author's closure)--Principal conclusions: Three lines of thought are initiated in the paper: A method of rating the volume of a river-deposit at the shoreline by comparison with the average area subject to erosion; the values accruing to adjacent beaches by diverting the discharge of a river from a drowned valley to the shoreline itself; and a general view of the relations of precipitation and runoff to the amount of material brought within the sphere of use for beach-nourishment.

In the second paragraph of his discussion, Mr. BROWN gives his observation as to the principal conclusion reached by the author. It is pertinent, therefore, that in conjunction with depositing material subsequent to 1922 at the shoreline and at a rate approximately proportional to the intensities of rainfall and discharge, the following is also brought to the attention of the reader.

(1) Prior to 1921, relatively little material transported by this stream reached the shoreline, due to the impounding capacity of a large area representing conditions of a drowned valley and located at a considerable distance to the rear of the waters of San Pedro Bay. The discussion apparently fails to recognize the changes in river-alignment and conditions of discharge within the Long Beach Area as reviewed in the basic paper. Formerly deprived of the greater percentage of debris deposited in the vicinity, the shoreline, since 1922, has been the recipient of practically all the material thus diverted and susceptible of deposit under the influence of natural forces active at the new point of discharge.

Obviously the recently completed flood-control dams located as shown on the map of Figure 1 also have the effect of depriving the shoreline of a large share of eroded material. It should be noted, however, that in the interim prior to construction of the dams, the shoreline had enjoyed an abundant supply not previously reaching it under natural conditions of river-discharge. With reference to the reduced supply of sediment, where impounded by the dams, it is believed that the paved, straightened, and otherwise improved stream-channels will transport the lesser volume of debris more rapidly toward the sea than ever before. Prior to such improvement the flow of debris was decidedly spasmodic in its progress seaward.

(2) The objective of the study, as indicated in the title, is to aid in establishing a relation between the forces and agencies responsible for producing shoreline and beach-material, which will facilitate a rational consideration of other similar problems in which estimates of such production are a prime requisite. Further study will doubtless afford more accurate data upon which to base the average percentage of area of a given watershed, ordinarily subjected to erosive effect from an average annual precipitation.

One of the principal sections of the paper therefore is that given in paragraphs 18 and 19, in which is discussed the relation between the estimated eroded area and the volume of deposit made under certain conditions at the shoreline.

Volume of delta-deposits--It is of importance to recognize that the estimates submitted by the author in Table 1 under the column of "Deposits at the shoreline," and those cited by Mr. BROWN in reference to the same subject, are of an approximate character. It may be equally true that the estimates are the best obtainable from existing data.

The yardage given in the Table represent distributions made from data furnished in the reports of responsible agencies which have collaborated in searching investigation and preparation of plans for flood- and debris-control and in shoreline and harbor-improvement of the Los Angeles and Long Beach areas.

It is thought quite probable that of the surveys and cross-sections from which calculations of sediment-volume were made by Mr. BROWN, the greater portion originated from the work of the collaborating agencies above mentioned. In a calculation based upon surveys and cross-sections culminating after the flood of March, 1938, Mr. BROWN has cited a figure of 6,474,000 cubic yards as an amount eroded from the banks and channel-beds.

It is interesting in this connection to examine paragraph 12 of the basic paper which shows the amount of 3,000,000 cubic yards removed from a paved section of the channel subsequent to the storm, in a length of the river-bed equal to approximately one-sixth of the total distance used in Mr. BROWN'S computation. Deposit of this sediment obviously must be regarded as a refill and as a portion of the total eroded volume. In the event the cross-sections were not adapted to the inclusion of the 3,000,000 cubic yards, the addition would increase the calculation to 9-1/2 million cubic yards. From a similar view-point, a consideration of the remaining five-sixths of the surveyed river-channel may change quite substantially the figure cited in the discussion.

A net differential area indicated by the comparison of two sets of cross-sections will provide a basis for estimating only that volume above the original section-line, taking no account of erosion and refill below the original profile.

SEDIMENT LOADS IN THE MOORE CREEK DRAINAGE-BASIN, IDAHO, 1939-40

S. K. Love and P. C. Benedict

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The Boise River Project in southwestern Idaho comprises an area of about 333,000 acres of highly developed agricultural land. Precipitation in the irrigated valley averages about ten inches a year which is too low to support any but desert vegetation. Water for irrigation during the growing season is obtained from Arrowrock Reservoir located on the Boise River four miles above Moore Creek, and from Deer Flat Reservoir near Nampa. The deposition of sediment in the river-channel, in irrigation-canals, and in farm-laterals has interfered with the normal operation of the irrigation-system and has occasionally required the expenditure of considerable time and money for removal of the deposited material.

Interest in determining runoff and sediment-loads from areas in the Boise River Drainage-Basin having different vegetative cover and subjected to different kinds of land-use practice led to an investigation by the Flood Control Coordinating Committee of the Department of Agriculture.

Stream-flow and sediment-loads were measured by the Geological Survey at 13 gaging-stations during the 18-month period ending June 30, 1940. Three of these stations were located on the Boise River, three were located on small tributaries of the Boise River (two of which were above Arrowrock Dam and one near Boise), and one was located on the New York Canal. The remaining six stations were located on Moore Creek and four of its tributaries near Idaho City. Records obtained from the stations located in the Moore Creek Drainage-Basin are the basis of the discussion in this paper.

Records of measurements made at all 13 stations have been issued in mimeograph form under the title "Discharge and sediment loads in the Boise River Drainage-Basin, Idaho, 1939-1940." A complete record of all measurements made by the Geological Survey, including tables of mechanical analyses and other data not given in the mimeographed report is being prepared for publication in a Water-Supply Paper.

The topography of the Moore Creek Drainage-Basin is rugged and mountainous. Elevations range from a maximum of about 8,000 feet in the headwaters of the creek to about 2,900 feet at the mouth. All of the area is included within the boundaries of the Boise and Payette National Forests and is covered with timber except where extensive logging-operations or serious burns have occurred. The mountains are composed chiefly of granites. Weathered granites are the source of most of the sediments in the streams. Stream-gradients are generally steep and range from about 40 feet per mile in the lower part of the basin to about 200 feet per mile in the upper part of the basin.

Five of the six stations in the Moore Creek Drainage-Basin were located on Moore Creek and its tributaries above Idaho City. The area drained by Moore Creek above Granite Creek consists of virgin timber, a portion of an extensive burn, old placer-diggings, and grazed land. The Granite Creek Area is characterized by an old burn, Bannock Creek, by virgin ponderosa-pine, Pine Creek, by a recent logging-operation of ponderosa-pine, and Elk Creek, by an old placer-operation, extensive burns, logging-conditions, and intensive grazing.

The sixth station was located on Moore Creek about six miles below Idaho City and below a large active placer-mining area. The largest and most extensive operation was carried on by means of a bucket-line dredge in the narrow valley between the two stations on Moore Creek. This dredge was operated 24 hours a day throughout the period of the investigation. Several other hydraulic placer-mines were operated in the foot-hills adjacent to Idaho City. The largest of these mines, the Gold Hill Placer, was operated only during the spring runoff when sufficient water could be diverted from Moore and Elk creeks. The smaller placer-mines were operated whenever water was available. A map of Moore Creek Drainage-Basin showing the locations of the six stations and the approximate areas in which recent large-scale placer-mining has been conducted on both Moore Creek and Grimes Creek are shown in Figure 1.

The type of gaging-structure established at each of the six stations depended on the drainage-area characteristics and the probable maximum discharge expected. Broad-crested wooden weirs with overfalls were constructed at three stations, a broad-crested concrete weir without overfall was installed at one station, and artificial rock-controls were utilized at two stations. Measurements of discharge were made with current-meters in accordance with the standard practices of the Geological Survey, except when flows were too small to be obtained in the ordinary manner. Measurements of small flows were made with portable V-notch and Cippoletti weirs.

Measurements of runoff and sediment-loads were complicated by diversions above three of the stations, a part of the flow being by-passed around the measuring sections. The station on Elk Creek was moved upstream prior to the spring runoff of 1940 to more nearly represent the runoff and sediment-load characteristics of the drainage-basin by eliminating the effects of diversions and placer-operations. At the same time, the station on Pine Creek was moved upstream above a proposed placer-development.

The maximum discharge in Moore Creek, as indicated by long-time records for the station at the mouth of the creek, was a little smaller in 1939 and a little larger in 1940 than the average

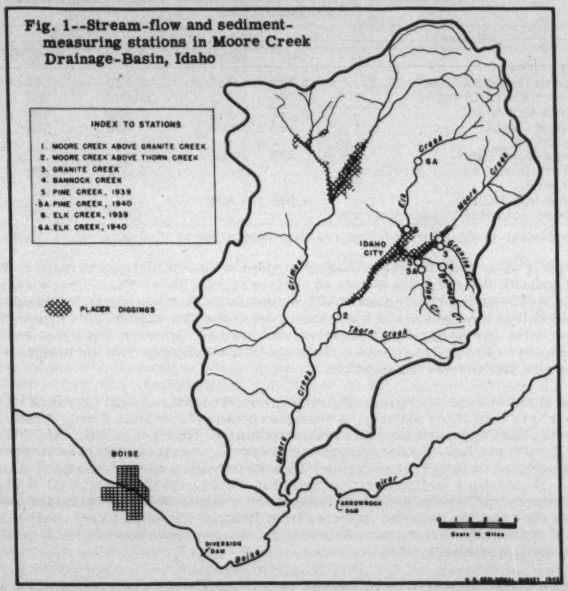

Fig. 1--Stream-flow and sediment-measuring stations in Moore Creek Drainage-Basin, Idaho

maximum for the previous 25 years. The mean annual discharge for both years was below the mean for the 25-year period.

Sediment-samples were collected by means of three types of sampling-apparatus from foot-bridges constructed at the gaging-stations. Integrated samples were collected at stations with overfall sections with a pint bottle in a frame with a rigid handle. The bottle was fitted with a rubber cap having a 3/4-inch hole and a small copper tube to vent the air during filling of the bottle. Successive lowerings through the overfall were made across the weir until the bottle was nearly full of water and sediment collected from all points from top to bottom in each vertical.

At stations without overfall sections integrated samples were collected in much the same manner as at the overfall sections except that it was not possible to obtain water and sediment from points closer than 0.2 foot above the bottom. The horizontal type of integrating sampler used at these stations also had a tube to vent the air during filling.

The third type of sampling-apparatus was the Tait-Binckley sampler with which point-samples were collected to determine the concentration and particle size of sediment at several points in the cross-section.

A summary of the total sediment loads measured at the six stations during the spring runoff-periods in 1939 and 1940 is given in Table 1. The data show that the largest loads, proportional to the drainage-area, were carried by Granite Creek in 1939 with a total of 610 tons per square mile, and by Pine Creek in 1940 with a total of 1,200 tons per square mile. The smallest loads were carried by Bannock Creek both in 1939 and in 1940 with 3.1 and 162 tons per square mile, respectively.

Table 1--Sediment-loads measured during spring runoff of 1939 and 1940, February to June

Station	1939		1940	
	ton	ton/sq mi	ton	ton/sq mi
Moore Creek				
Above Granite Creek[a]	5,020	136	6,230	168
Above Thorn Creek[a]	17,000	143	36,500	307
Granite Creek	2,930	610	1,950	406
Bannock Creek	14	3.1	728	162
Pine Creek				
Near Idaho City[a]	587	90	.....	.....
Above Barry Placer diversion[a]	.....	.....	7,350	1,200
Elk Creek				
Near Idaho City[a]	9,090	408	.....	.....
Above Gold Hill Placer diversion	.....	.....	2,820	215

[a]Sediment-loads affected by appreciable regulation or diversion above station.

A summary of monthly sediment-loads measured at the six stations is given in Table 2. These data indicate that the loads measured at Moore Creek above Thorn Creek were a little smaller during the spring-runoff months of 1939 and somewhat larger during the spring-runoff months of 1940 than the sums of the loads measured at the five stations above Idaho City during the same periods. During periods of moderate and low flow, however, the loads measured at Moore Creek above Thorn Creek were usually considerably larger than the combined loads measured at the five stations above Idaho City.

Graphs of mechanical analyses in Figure 2 show that during the spring runoff of 1939 from about 60 to 90 per cent of the material in samples collected from Pine Creek, Moore Creek above Granite Creek, Elk Creek, and Granite Creek consisted of particles greater than 100 microns in diameter. Graphs in Figure 3 show that during the spring runoff of 1940 over 80 per cent of the material in samples collected from Granite, Pine, and Bannock creeks consisted of particles greater than 100 microns in diameter, and that over 70 per cent of the material in samples from Pine and Bannock creeks consisted of particles greater than 1,000 microns in diameter. Although the analyses show that the material collected from Bannock Creek was very coarse, it should be pointed out that this coarse material was found only in samples collected over a period of a few days during the last of March, 1940.

The sediment-loads measured in Moore Creek above Thorn Creek, on the other hand, consisted almost entirely of fine material. Graphs of mechanical analyses show that from 45 to 55 per cent of the material in samples collected at this station during the spring runoff of 1939 and 1940 consisted of particles less than five microns in diameter and that from 80 to 90 per cent of the material consisted of particles less than 50 microns in diameter.

A relatively large amount of sediment consisting of fine material was contributed to Moore Creek between the five stations above Idaho City and the station on Moore Creek above Thorn Creek during certain periods, particularly during periods of moderate and low flow. The amount of unmeasured inflow between the five upper stations and the lower station on Moore Creek above Thorn Creek is small and can be neglected as a source of sediment. The only large active source of sediment during the periods of low flow was the placer-mining. Part of the sediment was contributed by placers on Elk Creek just above the gaging-station (No. 6 on the map) and part by

placers below stations 1, 3, 5, and 6. The sediment-loads resulting from these operations appear to be largely responsible for the increase in the loads measured at the station on Moore Creek above Thorn Creek during periods of low flow.

Table 2--Monthly sediment-loads in tons measured at stations near Idaho City

Month	Moore Cr. above Granite Cr.	Granite Creek	Bannock Creek	Pine Creek	Elk Creek	Total	Moore Cr. above Thorn Cr.
1939							
Jan.	2.3	0.3	0.09	0.9	2.2	5.8	109
Feb.	12	2.3	0.5	1.6	8.1	24	1,270
Mar.	2,730	2,060	1.4	364	2,950	8,110	5,330
Apr.	1,540	802	7.7	220	2,220	4,790	3,790
May	720	68	3.2	1.4	2,200	2,990	4,390
June	23	0.8	0.8	0.2	1,710	1,730	2,240
Total	5,030	2,930	14	588	9,090	17,600	17,100
1939							
July	9.2	0.3	0.2	0.06	615	625	716
Aug.	2.7	0.2	0.08	0.04	104	107	211
Sept.	9.6	0.3	0.1	0.1	215	225	314
Oct.	3.2	0.2	0.09	0.08	701	705	474
Nov.	8.2	0.5	0.1	0.06	351	360	1,200
Dec.	14	1.6	0.5	0.4	736	752	1,800
Total	47	3.1	1.1	0.7	2,720	2,770	4,720
1940							
Jan.	19	11	0.5	1.0	365	396	2,520
Feb.	170	413	1.8	356	141	1,080	3,760
Mar.	2,740	1,220	443	5,780	661	10,800	12,400
Apr.	2,360	272	282	1,130	1,220	5,260	8,520
May	928	11	1.1	71	811	1,820	8,250
June	30	0.8	0.4	15	102	148	3,530
Total	6,250	1,930	729	7,350	3,300	19,500	39,000
Grand totals	11,300	4,860	744	7,940	15,100	39,900	60,800

It is apparent from the mechanical analysis data and the information in regard to placer-mining activity that only a small part of the actual material carried past the stations above Idaho City was measured at the station on Moore Creek above Thorn Creek. Most of the coarse sediment carried past the upper stations was deposited in the deep pools behind rock-dikes formed by tailings from the mining-dredge. These dikes form deep pools which act as settling-basins because of the low velocity through them. The bulk of the fine material carried past the station on Moore Creek above Thorn Creek was derived from mining-operations within the placered area.

Most of the sediment passing the station on Moore Creek above Thorn Creek during 1939 and 1940 was too fine to settle out appreciably in the larger irrigation-canals. During earlier years, however, when less adequate control-measures were taken to retain the coarse materials within the placered area near Idaho City, there is reason to believe that a large amount of coarse sediment was carried downstream and was eventually discharged into the Boise River.

Grimes Creek carries large but unmeasured loads of sediment into Moore Creek 1-3/4 miles below the station above Thorn Creek. Placer-operations of considerable magnitude were carried on in the Grimes Creek Drainage-Basin during the period of the investigation and for several years prior to it. No sediment or stream-flow measuring station was established on Grimes Creek or its tributaries and therefore no estimate can be made of the amount of sediment contributed by this stream. However, the sediment-content of a few samples collected at irregular intervals from Grimes Creek just above its mouth, the appearance of the water in the two streams, and the presence of large deposits of sand in Grimes Creek and in Moore Creek below the junction contrasted with the sand-free channel in Moore Creek above Grimes Creek, all suggest that the sediment-loads carried into Moore Creek from Grimes Creek during the period of the investigation may have been larger than the loads measured at the station on Moore Creek above Thorn Creek, and that the material was considerably coarser.

Records show that the largest loads per unit of drainage-area measured in the Moore Creek Drainage-Basin were carried by Granite Creek in 1939 and by Pine Creek in 1940, and that the smallest loads per unit of drainage-area were carried by Bannock Creek both in 1939 and 1940.

Mechanical analyses show that the greater part of the loads measured at the stations above Idaho City consisted of coarse material, and that the loads measured at the station on Moore Creek above Thorn Creek consisted almost entirely of fine material. The rock-dikes and pools constructed in the dredged area by the placer-mining operators were effective in retarding the removal of coarse material from the area during the period of the investigation. It is probable, however, that in those spring periods during which the runoff is greater than that measured in

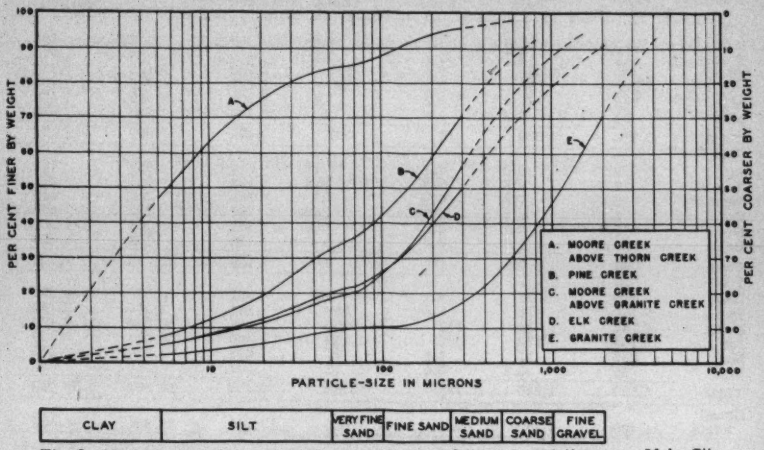

Fig. 2--Mechanical analyses of material carried past five gaging-stations near Idaho City during spring runoff of 1939, based on United States Bureau of Soils classification

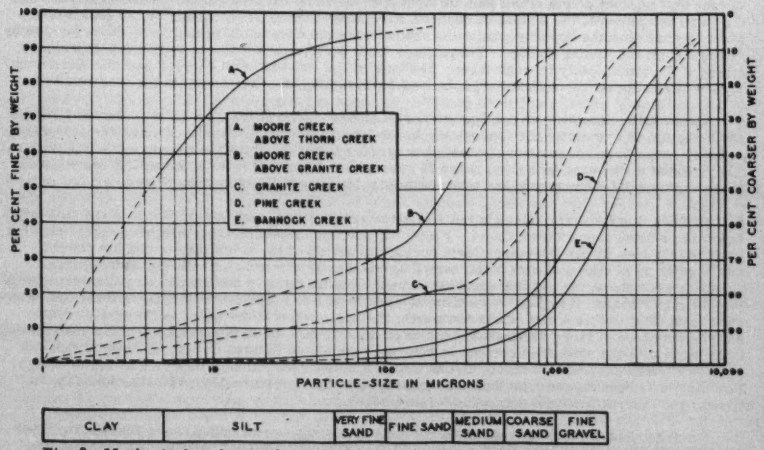

Fig. 3--Mechanical analyses of material carried past five gaging-stations near Idaho City during spring runoff of 1940, based on United States Bureau of Soils classification

1939 and 1940, the loads of coarse sediment carried past the station on Moore Creek above Thorn Creek would be very much greater than were measured during the period of the investigation.

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DISCUSSION

LOUIS M. GLYMPH, JR. (Soil Conservation Service, Washington, D. C.: communicated)--The authors have reported on a very interesting program of sediment-measurement. The large number of samples collected during the program are doubtless sufficient to indicate the general relationship between the sediment-loads at the several sampling-stations under conditions which prevailed throughout the period of measurement. It may be, however, that those collected at overfall stations tend to give comparatively larger proportions of coarse sediment and too large total-load values.

Under conditions prevailing at an overfall station, the coarse material which normally moves through the stream cross-section nearer the stream-bed and at slower rates than the finer material becomes as susceptible to sampling as the finer material. If it is included with the sample from which total load is computed and assigned a velocity comparable to that of the water or the finer material, the final volume-figure may be too great. Samples collected at such stations may contain proportionately larger amounts of coarse material than those collected at the other sites because of the limitations of suspended-load sampling-techniques in measuring sediment moving along the stream-bed. These factors could account for a part of the difference in amount of material measured at the stations above Idaho City and at the station on Moore Creek above Thorn Creek, but it does not seem probable that they offer a complete explanation of the discrepancies observed at these stations.

ISLAND-FORMATION AND CHANNEL-FILLING ON THE UPPER WABASH RIVER

Gunnar M. Brune

Introduction--About 70 years ago, intensive settlement and cultivation began in the upper Wabash River Drainage-Area in Indiana. Along with this settlement came a number of developments of great significance to the inhabitants of the upper Wabash Valley. As the hillsides were cleared of their forest-cover and put to cultivation, more and more sediment was contributed to the river. The river-banks also were cleared, and as a consequence the river began to erode its banks and widen its channel. Many mill dams and water-supply dams were built along the river. In other places fills, dumps, and bridges came into existence and encroached upon the normal channel cross-section. As a result of some or all of these factors, islands and other channel-fill deposits grew at an alarming rate. Residents of certain parts of the valley began to suffer from more frequent and more severe floods.

It may be well to explain at this point that there are many different kinds of islands. First, the islands may be classed as residual or accretionary. A residual island is formed by an avulsion of the river in which it takes two channels instead of one. Such an island may be composed of bed-rock or stratified flood-plain sediment. An accretionary island, on the other hand, gradually builds itself up in the middle of the stream. Some islands may belong in both of these categories, that is, they may be residual islands that have been enlarged by accretionary deposits at either end.

Accretionary islands may be further classified according to origin as crossing-bars, bend-bars, and those due to random accidental obstructions. Crossing-bars are common in many ditched channels, and on streams with a heavy bed-load such as the upper Mississippi in Wisconsin and Minnesota. Bend-bars occur on the Ohio River, among many places, and are sometimes prominent in slack water near the head of channel-type reservoirs. Islands due to random obstructions, such as bridge-piers or stranded drift-wood, may occur almost anywhere.

Residual islands also may be subdivided into those due to ox-bow cut-offs, and those due to other types of channel-avulsions. This distinction is obviously based more on the type of stream involved, rather than on any difference in the island-features, except that the latter are usually more irregular in outline and size. Ox-bow cut-offs are common on most actively meandering streams. Islands due to other types of channel-avulsion seem to be most common and are best

preserved where there is an abundant supply of bed-load too coarse to be moved except in very high flows, or where divided channels are preserved by accidental encounters with bed-rock ledges buried in the alluvial valley-fill. (These subdivisions of the two main types of islands have been suggested in personal communication from STAFFORD C. HAPP concerning the results of unpublished studies on the Delaware River.)

Islands may also be classified as pre-modern and modern. Pre-modern islands are those that existed before the balance of Nature was upset, before accelerated erosion and sedimentation began, or, in other words, before intensive settlement of this area began. Such islands usually possess some sort of a soil-profile, even though the soil may be very young, and they sometimes support a growth of very old trees. Modern islands, on the other hand, are those that have formed since the area was settled by man and are a result of accelerated sedimentation. They are composed chiefly of gravel and sand, they do not possess a soil-profile, and, although they may support trees, these trees may not be termed "virgin timber." The trouble-makers in this area are modern islands of the accretionary type, together with closely-related bars and other types of channel-fill deposits.

Some previous work has been done in the study of islands and channel-fill deposits on the upper Wabash. In 1914 BALL and others [see 1 of "References" at end of paper] made a study of the effect of bridge-piers on the current of the Wabash River. Later [1925] a study was made of obstructions in the Wabash River at Peru [2]. By 1925 there were 12 islands in the river at Peru, which in addition to numerous fills, dumps, bars, bridge abutments, piers, and superstructures, had seriously increased the frequency and severity of floods in Peru. In 1930 Peru completed its flood-control program, including the removal of the 12 islands and other channel-obstructions and the raising of a bridge.

The object of this study was threefold: First, to determine to what extent the upper Wabash River is filling or enlarging its channel: second, to evaluate the effects of this process on flood-frequencies; and third, to make a study of the possible causes of the phenomena observed. The work was done as part of a flood-control survey made by the Department of Agriculture. The studies of flood-heights were not essential to the explanation of the island-formation and channel-filling, although they were related from the standpoint of the flood-control survey.

The section chosen for detailed study was the 100-mile stretch between river-mile 312.0 at Lafayette and river-mile 412.0 at Huntington (see location-map, Fig. 1). The field-work was carried out from September, 1940, to January, 1941.

Method of study--In the summers of 1929 and 1930, the United States Army Engineers mapped the flood-plain of the Wabash River from Terre Haute to Huntington, on a scale of one inch to 1,000 feet and with a contour-interval of ten feet. In making these maps, cross-sections of the river-channel were taken at one-half-mile intervals. At the time these maps were made, islands existed on 10.3 per cent of the length of this section of the river. In a preliminary study, 17 islands were selected at random, and changes in their shape and size were sketched on the maps. During the 10.3-year period since the maps had been made, these islands had grown from an average size of 11.1 acres to 12.7 acres, or 14.4 per cent.

The detailed study was made in the following way. From the maps, nine of the channel cross-sections, at approximately 10-mile intervals, were relocated as accurately as possible and resurveyed. These nine cross-sections were extended across the entire valley. Upstream and downstream from each valley cross-section, four channel cross-sections were resurveyed also, except in one case, where only one additional channel-section was measured. A total of 42 valley and channel cross-sections were made. Borings with a soil-auger were made on the valley cross-sections at 100-foot intervals to determine the depth of modern sediment.

The valley and channel cross-sections were plotted. One of these plotted cross-sections, considerably reduced, is shown in Figure 2. The sediment measured in flood-plain borings was the modern sediment that had accumulated since accelerated sedimentation began, which is believed to be an average period of 70 years for this entire area. This depth of sediment was divided by seven to obtain the approximate depth of sediment deposited on the flood-plain during the 10.3-year period covered by the channel surveys. It was found that in most cases flood-plain sediment was not of sufficient depth to show on the plotted cross-sections.

In computing the changes in flood-frequency, flood-lines were drawn on the cross-sections of 1930 and 1940 to represent total, 75 per cent, 50 per cent, 25 per cent, and 5 per cent flooding of the bottom land (see Fig. 2). The flood-stage of 1913 was used as "total flooding of the bottom

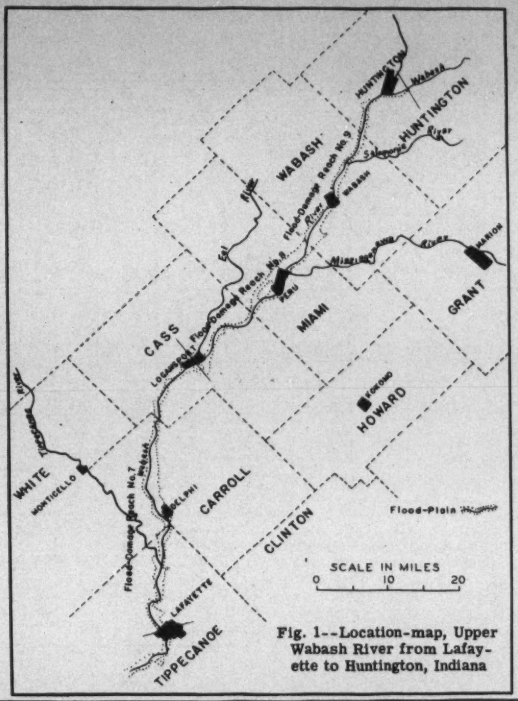
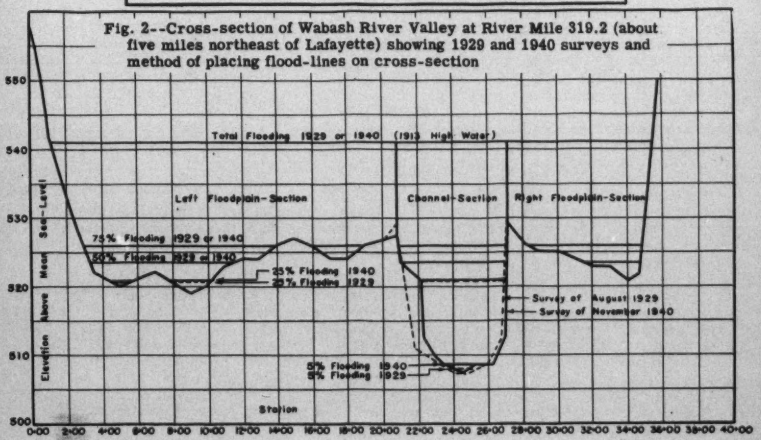


Fig. 1--Location-map, Upper Wabash River from Lafayette to Huntington, Indiana

Fig. 2--Cross-section of Wabash River Valley at River Mile 319.2 (about five miles northeast of Lafayette) showing 1929 and 1940 surveys and method of placing flood-lines on cross-section



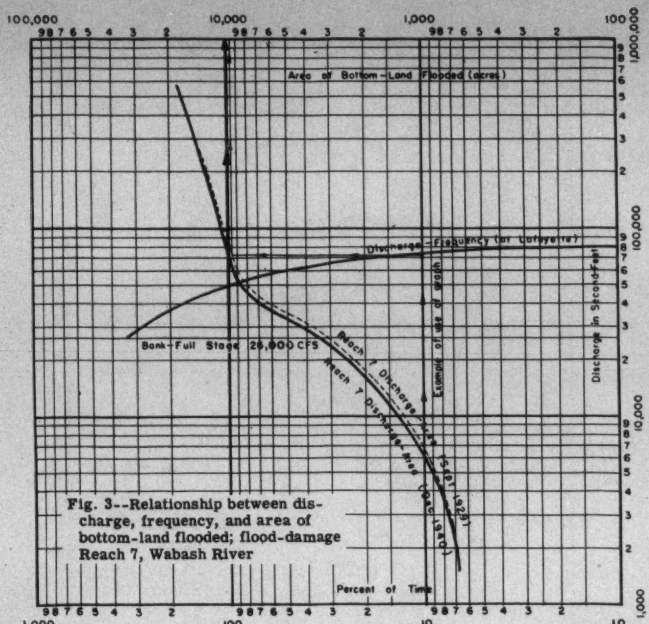


Fig. 3--Relationship between discharge, frequency, and area of bottom-land flooded; flood-damage Reach 7, Wabash River

land," although it included some terrace land also. The slope of the river, hydraulic radius, and cross-sectional area were determined for each of the five stages on each of the cross-sections, in 1930 and 1940. Then, using the MANNING formula, and assuming a coefficient of friction, discharges were determined for each stage on each cross-section in 1930 and 1940. The coefficients of friction which were used, both for the cross-sections of 1930 and 1940, were 0.030 for a clear channel, 0.035 for a channel obstructed by an island, 0.040 for a cleared flood-plain, and 0.050 for a flood-plain covered with trees and brush. Discharges were computed for channel and flood-plain separately at each cross-section. For each group of five cross-sections, the discharges were averaged and then added to the flood-plain discharge of the valley cross-section to obtain the total discharge.

The 100-mile stretch was divided into three reaches, as shown in Figure 1. The figures for the discharge in each reach were plotted against area flooded (Figs. 3 and 4). Discharge-frequency curves were plotted in the same figures. Then, with the aid of these graphs, the average change in area of land flooded, for floods of all frequencies between bank-full stage and a 100-year flood, was determined for each reach.

Results--It was found by planimeter-measurements of the plotted cross-sections that in all three reaches, the annual net gain of flood-plain sediment was negligible. Sediment was usually deposited on the flood-plain in the form of fans, splays, or vertical accretion deposits. Flood-plain scour, on the other hand, tended to remove these deposits, and sometimes some of the old flood-plain soil. On the flood-plain the forces of scour practically balance those of deposition, with the result that flood-plain sedimentation has had a negligible effect on flood-stages.

In respect to channel-sediment, however, there is a different story. It was found that in Reach 9 (from Huntington down to the Mississinewa River) the river-channel has been enlarging

itself at an average annual rate of 85.2 acre-feet. In Reach 8 (Mississinewa River down to the Eel River) the channel grew larger at an average annual rate of 33.5 acre-feet. In Reach 7 (from the Eel River down to Lafayette) the channel has been filling at an average annual rate of 371 acre-feet of sediment. Stream-bank erosion and bed-scour tend to enlarge the channel and remove sediment. On the other hand, island-formation and channel-fill deposits reduce the size of the channel. In Reach 9 the forces of erosion were stronger than those of deposition. In Reach 8 they were also stronger, but to a lesser degree. In Reach 7 the forces of deposition became much stronger than those of erosion in the channel.

The channel-measurements indicated that, in Reach 9, the river bed has degraded about 0.5 feet in ten years, in Reach 8 it has cut down about 0.9 feet in ten years, and in Reach 7 it has aggraded about 0.7 feet in 11 years.

As for the effect of these changes on flood-stages, the following results were found. In Reach 9, on the average, there is an annual decrease of 9.04 acres flooded by the average of floods of all frequencies. This is equivalent to an annual decrease of 0.09 per cent in the area of land subject to flooding. In Reach 8 there is an annual increase in area subject to flooding of 1.08 acres, or 0.02 per cent. In Reach 7 there is an annual increase of 60.03 acres, or 0.44 per cent.

Discussion--TODD and ELIASSEN [4] point out that certain rivers, such as the Yellow and the Colorado, scour their beds when the discharge is increasing and refill them upon a decreasing discharge. In these cases the bed-material is relatively fine and a considerable quantity of the material goes into suspension with an increase in discharge. On the other hand, the

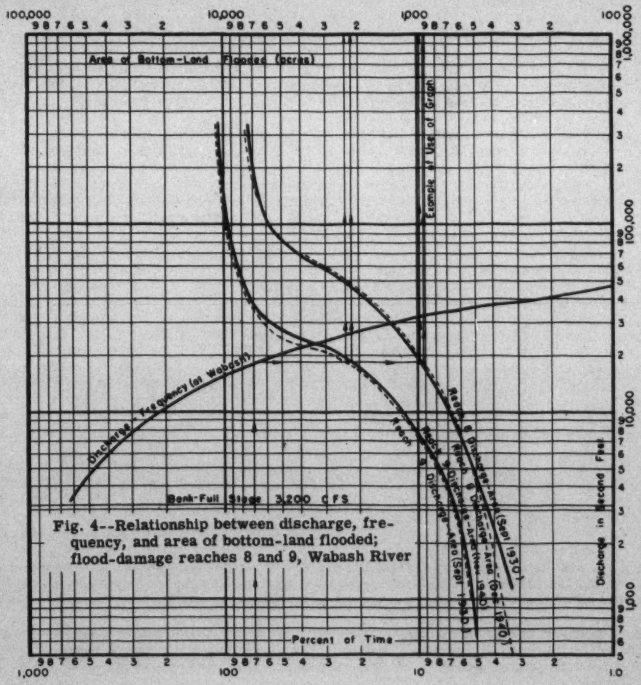


Fig. 4--Relationship between discharge, frequency, and area of bottom-land flooded; flood-damage reaches 8 and 9, Wabash River

Mississippi and the Yangtzekiang tend to raise their beds when the flow is increasing and to scour the deposited material when the river is falling. In these cases the raising of the bed is only local, that is, at the crossings, where material is deposited as a result of scour in the immediate upstream pool. During the falling and low stages the water-surface slope is steeper over the crossings than in the pools and scour of the crossings takes place. The pools immediately downstream from the crossings are thus filled.

Such seasonal fluctuations probably are not significant on the upper Wabash River. At any rate, both the survey of 1929-1930 and the survey of 1940-1941 were made in dry seasons, when the discharge was low. Any seasonal variation that may exist, therefore, should not affect the net changes measured.

It is apparent that the problem is serious only in Reach 7, where, if island-formation and channel-filling continue at the same rate, at the end of 100 years they will cause an increase of 44 per cent in the average annual flood-damage. It is of interest to note that, while the channel in Reach 8 has become slightly larger during the period of study, the area subject to flooding has become larger instead of smaller. This illustrates the fact that, although the channel as a whole may be enlarging itself, the growth of local obstructions such as islands and bars at a few points may cause an increase in the area subject to flooding

The rate of channel-filling in Reach 7, 0.7 feet in 11 years, is not unusually high. Studies made by the Sedimentation Division of the Soil Conservation Service on the Rio Grande, for example, show that just below the junction with the Rio Puerco the floodway rose four to five feet in the nine-year period between 1927 and 1936, and upstream from Elephant Butte Reservoir it was built up 3-1/2 to four feet in the ten-year period between 1926 and 1936 [5]. The high agricultural value of the bottom land along the upper Wabash, however, makes an annual increase of one-half of one per cent in flood-damage a serious matter.

A study of the Kickapoo River, in Wisconsin, also made by the Sedimentation Division of the Soil Conservation Service, indicated an average rate of river-bed aggradation of about one foot in 22 years, which is slightly less than the rate for Reach 7 of the upper Wabash [6]

The causes of island-formation and other forms of channel-deposition on the Upper Wabash are numerous and interrelated. First, the gradient of the river appears to be important. In Reaches 8 and 9 (from Huntington down to Logansport) the gradient is fairly constant, averaging 2.33 feet per mile. Just below Logansport it increases sharply to 5.47 feet per mile, and then decreases to 0.38 foot per mile at Lafayette. It is in this reach of rapidly-decreasing gradient, Reach 7, that the channel-fill deposits and island-formation have caused the greatest increase in flood-stages in the section studied.

Another cause of island-formation is an abundance of sediment entering the river. There is no doubt that more sediment has been released annually to the river since man began to settle this area than before. Some of the sediment comes from the erosion of cultivated fields and highway banks. Most of the sediment that forms islands and other channel-fill deposits, however, probably is derived from channel-enlargement on smaller tributaries upstream. This enlargement may take the form of bank-erosion, either in the flood-plain alluvium or undercutting the valley-sides, or deepening of drainage-ditches. In other cases, bridges with too many piers or too low a superstructure may impede the flow of water. In times of flood, the water will build up a head upstream from such bridges and pass beneath them with great velocity, scouring much material from the river-bed. All this material passes downstream to contribute to the formation of islands and other deposits.

Islands will form more readily if an unusual amount of sediment is contributed in a short time. For instance, if a dam, which has been collecting sediment for years, suddenly breaks, the sediment will move downstream in the form of sand and gravel-bars and will tend to start the formation of islands.

A general or average condition is not required for island-formation. In Reach 9, for example, where more sediment was removed from the channel than was deposited in it, many islands are known to have been growing. These may have been built, of course, from sediment derived from a tributary or from a nearby, localized source, either by bank-erosion or channel-scouring.

Another factor that is undoubtedly important in the deposition of bed-load material is the widening of the channel. WHIPPLE [7] points out the fact, in regard to the Missouri River, that contraction of the channel increased the capacity for bed-load and vice versa. There has been

moderate stream-bank erosion and consequent widening of all of the upper Wabash River since the banks were cleared by white men. This widening probably has been important in reducing the capacity of the river for bed-load and starting the formation of islands.

Another immediate cause of these phenomena is unusual eddies or changes of velocity in the flow of a river. Bridge-piers give rise to great disturbances in the velocity and the flow of water, especially if the ends of the piers are not shaped correctly. Eddies also are formed by the junction of two streams. In some instances a small stream of high velocity entering the Wabash River will deposit its load in the form of a delta, which may grow to be an island.

Whatever the initial cause of its formation, once an island or bar has gained sufficient height to remain above water most of the year, its growth from that point on is more rapid. Vegetation begins to establish itself, beginning with species that can endure very wet conditions. Usually wildrice is first, then come cockleburs, then willow and sycamore trees. As soon as vegetation gains a foothold, the rate of deposition of sediment on the island increases; the more dense and firm the vegetation becomes, the more sediment is caught. Thus the island is built up until it has reached a height beyond which ordinary floods do not rise. Once an island has become established, it sets up disturbances in the flow of the water, especially at its downstream end, and hence tends to extend the downstream end in addition to increasing its height.

Summary--A study was made of the effect of island-formation and other channel-fill deposits on flood-stages during the ten-year period 1930-1940 in the upper Wabash River Valley between Huntington and Lafayette. In this area the amount of flood-plain sediment-deposits is negligible. In the upper and middle reaches of the section studied the channel has become larger, while in the lower reach the channel has filled considerably. The effect of these changes has been to cause, in the upper reach, an annual decrease of 0.09 per cent in the area of land affected by the average of floods of all frequencies. In the middle reach there has been an annual increase of 0.02 per cent, and in the lower reach an annual increase of 0.44 per cent.

The sediment that forms islands and other channel-fill deposits is derived chiefly from channel-enlargement on smaller tributaries upstream, and less from the erosion of cultivated fields and highway banks. An unusually high rate of contribution of sediment, such as is caused by the breakage of a dam, is favorable to island-formation. Islands, however, may form even though there is not an excess of sediment in the channel. The rapidly-decreasing gradient in the lower reach appears to be an important cause of island-formation and other deposits. Widening of the channel has probably reduced the capacity of the river for bed-load; so also have the unusual disturbances of the velocity and flow of the river. Once an island has begun to form, vegetation will cause it to grow more rapidly.

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THE USE OF MASS-CURVES IN EVALUATING SUSPENDED-LOAD OBSERVATIONS ON SMALL PIEDMONT STREAMS

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Introduction--In connection with the design of certain proposed river-works, such as canals and reservoirs, information on the sediment-load of the stream in question is necessary. In the absence of a reliable and convenient method of estimating the bed-load of the stream, observations, in the past, usually have been confined to sampling of only the suspended matter. As a rule, such observations are conducted only over a period of one to five years and, consequently, may not be representative of conditions that may prevail throughout the useful life of the proposed structure. The estimated silting-rate of a reservoir, for example, may be based, in the absence of long-term data, on an average annual suspended load obtained from two or three years of record. The reliability of this value of the average load depends, primarily, on whether the factors controlling the supply of sediment to the stream were normal during the period of sampling.

In the Piedmont Region of the Southeast, measurement of the sediment-load of a stream considered typical of that region has shown that the largest percentage of the load consists of fine material [see 4 of "References" at end of paper]. The principal factors controlling the supply of this material, which has been termed "wash load" by EINSTEIN, ANDERSON, and JOHNSON [2], are topography, soils, shape and size of watershed, land-use, vegetal cover, surface and underground storage, soil-moisture, and intensity, distribution, and duration of rainfall. Also of importance are the characteristics of antecedent rainfall and the period of time since its occurrence. In any drainage-system, certain of these factors may be considered constant, whereas others have a seasonal variation, but at a certain season on a particular watershed, rainfall-intensity has been found to be the most important single factor influencing the amount of erosional debris that may enter the drainage-stream.

With rainfall playing such an important role in supplying most of the sediment that forms the suspended load of Piedmont streams, a consideration of the rainfall-characteristics during the period of suspended-matter sampling in comparison with long-term rainfall-records is of great importance. For example, Figure 1 shows curves of accumulative deviations of annual rainfall from the mean for two stations in the Piedmont where long-term precipitation-records are available. For each curve the ten-year moving average also is shown to assist the reader in better visualizing the general trend of the data. To the right of the mass-curves is a slope-diagram for the purpose of quickly determining the excess, or deficiency, of the annual rainfall. Examination of Figure 1 indicates that any suspended-load observations taken on streams in this region prior to 1923, in general, were taken during periods of greater-than-average rainfall, and consequently, above-average quantities of suspended sediment probably were transported. Following 1923, the trend was definitely one of deficient rainfall and, particularly since 1937, the deficiency has been the most serious on record.

Although the curves presented in Figure 1 show the general trend of total precipitation during the last 60 or more years, the total rainfall in itself does not give an index of the amount of sediment transported in the drainage-streams, any more than it gives an index of the amount of run-off. Because rainfall-intensity is the most important factor controlling the supply of suspended matter to streams in the humid region, a breakdown of total rainfall into various intensity classes gives a clearer picture of the trend of occurrence of erosion-producing rains. Such a summary is presented in Figure 2 for the Greenville, South Carolina, station. Here, as in Figure 1, mass-curves of cumulative deviation of rainfall from the mean, or an even value close to the mean, were utilized. This type of mass-curve moves in a generally-horizontal direction and makes it possible to enlarge greatly the vertical scale without throwing the curve off the paper. It also produces more definite points of tangency and a more readable curve [3].

Figure 2 shows, for the 21-year period from 1921 through 1941, mass-curves of rainfall computed from monthly totals of rains of various daily amounts. In addition to the mass-curve of total monthly rainfall, curves (Fig. 2-a) are shown for monthly totals of daily rains amounting to 2.00 inches and greater (Fig. 2-b), between 1.00 and 1.99 inches (Fig. 2-c), between 0.50 and 0.99 inch (Fig. 2-d), between 0.25 and 0.49 inch (Fig. 2-e), and between 0.0 and 0.24 inch (Fig. 2-f). The significant feature of such curves lies mainly in their slope and gives the excess or deficiency of rainfall. The slope-diagram to the right in Figure 2-a is for the purpose of readily determining these slopes. The vertical scale on the extreme left is used only for plotting the curves. The curves shown in Figures 2-b to 2-f are of importance in showing the effect of the various amounts of daily rainfall in affecting the shape of the curve of total rainfall (Fig. 2-a). It is of interest to observe that the curves for daily rains amounting to 0.49 inch and less (Figs. 2-e and 2-f) are

relatively constant, whether it is a wet or dry year. Unquestionably it is these rains of small amount, from which little or no surface-runoff probably results, that supply the necessary moisture for crops to survive even during periods of extended drought.

An examination of the curves for daily rains of 0.50 inch and greater (Figs. 2-b to 2-d), however, shows that these heavier rains mainly are responsible for the shape of the curve of total rainfall. In other words, whether the monthly or annual rainfall is above or below the normal rainfall depends on the occurrence or absence of a relatively few rains of high amounts. It is this type of rain that causes high rates of runoff and transports the bulk of the annual sediment-load from a watershed.

Mass-curves of rainfall and suspended load--In connection with research studies of the Soil Conservation Service [1], mass-curves of rainfall and suspended load were found to provide a valuable instrument in evaluating, and in some cases extrapolating beyond the period of actual record, the suspended-load data from three Piedmont streams. The data used in this analysis were collected by the Soil Conservation Service in cooperation with the United States Geological Survey and the North Carolina Agricultural Experiment Station [5] and include records on rainfall, discharge, and suspended load. The watershed map of the three streams (Fig. 3) shows the locations of the gaging and sediment-sampling stations, and also the locations of the rain-gages, records from which were used in the following analysis.

To illustrate in detail the methods employed, data from the West Fork of Deep River are used. Suspended-load observations were made on this stream from February, 1934, to September, 1940. Hourly amounts of rainfall at various gages in or near the watershed are available from

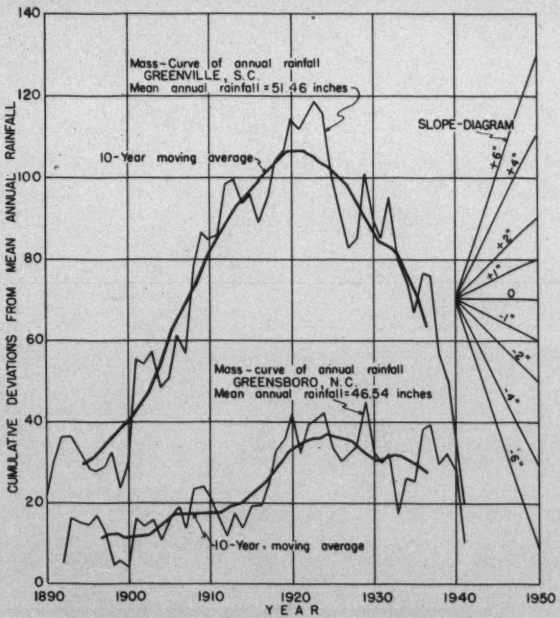

Fig. 1--Mass-curves of annual rainfall for United States Weather Bureau stations at Greenville, S. C., and Greensboro, N. C.

1928 to the present (1942). In the watershed itself, rain-gages were established and then discontinued, so that a record of rainfall at a single gage for the period covered by suspended-sediment sampling is not available. The locations of the various gages are shown in Figure 3 and the period of record covered by each gage is indicated in Figure 4.

A close examination of the records of rainfall and suspended load for the West Fork of Deep River showed that unless the hourly amounts of rainfall exceeded 0.20 inch, little or no suspended load was transported. Whether the amount of 0.20 inch is the exact dividing value between the occurrence or absence of an appreciable load, or whether it is constant throughout the year, is unimportant for most practical purposes, because the hourly rainfall was generally much less or much greater than this value.

In order to determine whether anything more than a general relationship existed between suspended load and rainfall, mass-curves of monthly suspended load and monthly totals of hourly

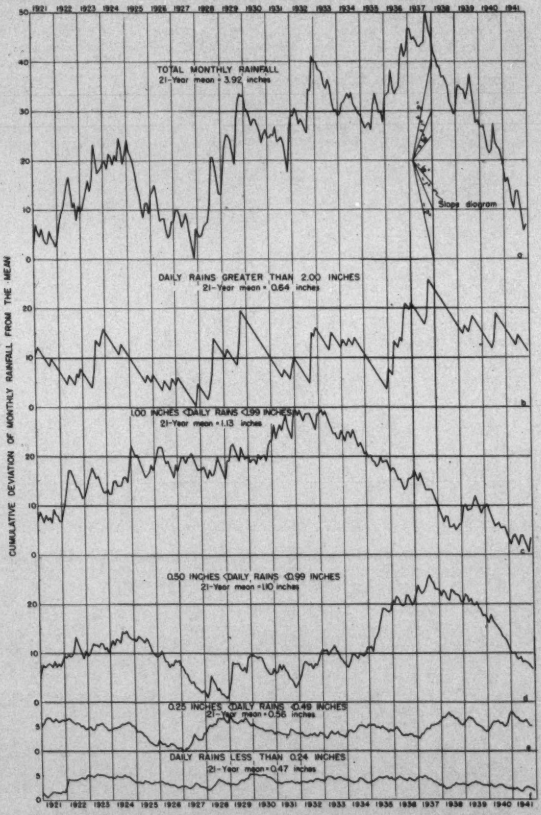
1921 1922 1923 1924 1925 1926 1927 1928 1929 1930 1931 1932 1933 1934 1935 1936 1937 1938 1939 1940 1941
CUMULATIVE DEVIATION OF MONTHLY RAINFALL FROM THE MEAN
TOTAL MONTHLY RAINFALL
21-Year mean = 3.92 inches
Slope diagram
DAILY RAINS GREATER THAN 2.00 INCHES
21-Year mean = 0.64 inches
1.00 INCHES ‹DAILY RAINS ‹1.99 INCHES
21-Year mean = 1.13 inches
0.50 INCHES ‹DAILY RAINS ‹0.99 INCHES
21-Year mean = 1.10 inches
0.25 INCHES ‹DAILY RAINS ‹0.49 INCHES
21-Year mean = 0.56 inches
DAILY RAINS LESS THAN 0.24 INCHES
21-Year mean = 0.47 inches

Fig. 2--Mass-curves of monthly rainfall of various daily amounts for United States Weather Bureau station at Greenville, S. C.

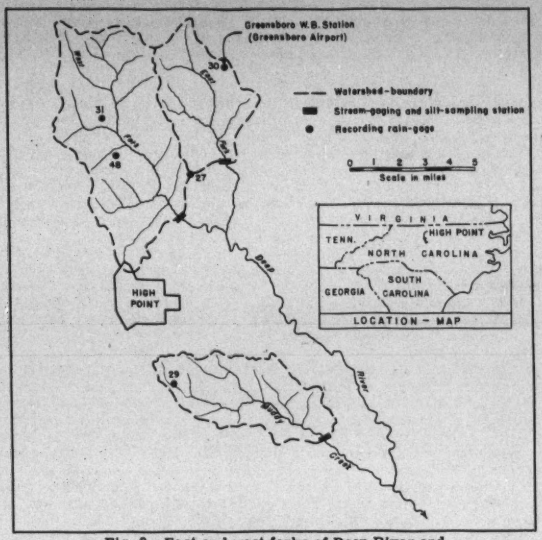

Fig. 3--East and west forks of Deep River and Muddy Creek watersheds

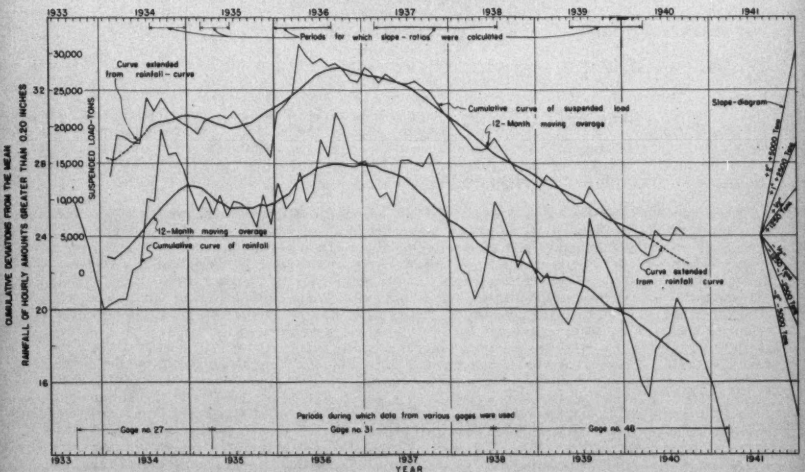

Fig. 4--Mass-curves of monthly suspended load and rainfall for west fork of Deep River

amounts of rain of 0.20 inch or more were prepared and are shown in Figure 4. To reduce the effect of the individual values and to eliminate seasonal variations, 12-month moving averages of these two mass-curves were computed. The similarity of the shape of these two curves is apparent, and suggests that a usable relationship between suspended load and rainfall might be developed.

Before proceeding further with the discussion of the use of these mass-curves, however, a description of their development is desirable. Using a computation table similar to Table 1, monthly totals of suspended load, Column (3), and rainfall, Column (8), are tabulated. The totals of these two columns are taken and the mean monthly load and rainfall computed. With respect to the suspended-load calculations, Column (4) shows the deviation of each monthly load from the mean. Column (5) shows the cumulative summation of these deviations. In order that all values in Column (5) would be positive, an arbitrary value of 5,000 tons on the first day of record (February 1) is assumed. The 12-month moving average of the mass-curve data shown in Column (5) is computed and recorded in Column (6).

By a similar step-by-step procedure, calculations are made also on the monthly deviations of rainfall from the monthly mean Column (9), the cumulative summations of these deviations Column (10), and a 12-month moving average Column (11). As is done in Column (5) for the suspended load, an arbitrary initial value on the first day of record (February 1) is assumed in order that all values in Column (10) would be positive.

In seeking a relationship between average curves of rainfall and suspended load, the fact that the slopes of the curves are their most significant characteristic suggests at once the possibility of computing the ratio of slopes at all points, and then determining whether these ratios can be represented for all practical purposes by a single arithmetic average. The procedure followed in the computation of such an average for the West Fork of Deep River data is illustrated in Table 1. By considering the monthly period between plotted points (Fig. 4) to be unity, the slope of the load-curve for each month is given by the differences of the ordinates of the curve [Column (7)]. By similar reasoning, the slope of the rainfall-curve for each month is given by the differences tabulated in Column (12). The ratio of the slope of the load-curve to the slope of the rainfall-curve for each month is shown in Column (13). Although not evident in Table 1, the slope-ratio was not computed for those periods where the slopes of the two curves were of opposite sign, or where the slopes of the curves were close to zero. The periods for which the slope-ratios were computed are indicated in Figure 4. The mean slope-ratio for the entire period of record is shown at the foot of Column (13). The significance of this ratio is that it represents the mean monthly deviation of suspended load per inch deviation of rainfall.

Application of mass-curve slope-ratio--To illustrate the reliability and limitations of applying a mean slope-ratio to the analysis of various suspended-load problems, data from the East and West Forks of Deep River and Muddy Creek are used. The application of the slope-ratio for the West Fork is illustrated in detail in Column (14) and (15) of Table 1. Thus, multiplication of the mean slope-ratio of 2,206 tons per inch by the slope of the rainfall-curve for each month in Column (12) gives a computed deviation of suspended load as in Column (14). This deviation, when added algebraically to the mean monthly load of 1,589 tons [see bottom of Column (2)] gives the computed suspended load for each month [Column (15)].

In connection with the calculations in Table 1, an additional explanation may be necessary. It is to be noted that the average curves of suspended load and rainfall (Fig. 4), begin and end six months from the beginning and end, respectively, of the actual period of record. The computations necessary in determining the computed suspended load for the period covered by the average curve of suspended load are shown in Table 1 between the heavy horizontal lines. By extending the record of computed load for six months at both the beginning and the end of this period, a direct comparison can be made between computed and observed load for the entire period of record (February, 1934, to September, 1940). To extend the record of computed load it is necessary first to extend the average curve of rainfall an additional six months at each end of the record. In Table 1 the necessary observed rainfall is tabulated in Column (8) above and below the heavy horizontal line. The deviations of these amounts from the same mean value (1.64 inches) used in the original calculations are recorded in Column (9). Using these values, the cumulative curve [Column (10)] is next extended in both directions. (The plot of these data is indicated by the dotted portions of the rainfall-curve shown in Fig. 4.) The 12-month moving average is computed [Column (11)] and the ordinate differences recorded in Column (12). By multiplying the average slope-ratio [obtained in Column (13)] by Column (12) and then algebraically adding these values to the mean suspended load (1,589 tons per month) the computed suspended load for the complete period of record is obtained as in Column (15). As would be expected, the computed loads

Table 1--Computation of mass-curves of suspended load and rainfall for West Fork of Deep River

Note: Data and computations for 1935-1939, are not shown.

		Suspended-load data					Rainfall data					Computed suspended load		
Year	Month	Monthly suspended load	Deviation from mean	Summations[a]	12-month moving average of column (5)	Differences in column (6)	Monthly totals of rains of hourly amounts of 0.20 inch or more	Deviation from mean	Summations[a]	12-month moving average of column (10)	Differences in column (11)	Ratio of slopes of load- and rainfall-curves, column (7) ÷ column (12)	Computed deviation of load, column (12) ×2206	Computed monthly load 1589+ column (14)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
		ton	ton	ton	ton	ton	in	in	in	in	in	ton/in	ton	ton
1933	Aug.	.....	.....	.....		.....	7.60[d]	+5.96	27.65	.....	.....	.....	.....	.....
	Sep.	.....	.....	.....	.....	.....	0.00[d]	-1.64	26.01	.....	.....	.....	.....	.....
	Oct.	.....	.....	.....	.....	.....	0.24[d]	-1.40	24.61	.....	.....	.....	.....	.....
	Nov.	.....	.....	.....	.....	.....	0.31[d]	-1.33	23.28	.....	.....	.....	.....	.....
	Dec.	.....	.....	.....	.....	.....	0.00[d]	-1.64	21.64	.....	.....	.....	.....	.....
1934	Jan.	.....	.....	5,000[b]	15,705[c]	.....	0.00[d]	-1.64	20.00[b]	22.93	.....	.....	.....	.....
	Feb.	9,604	+8,015	13,015	15,396[c]	.....	2.01	+0.37	20.37	22.79	-0.14	.....	- 309	1,280
	Mar.	7,462	+5,873	18,888	16,102[c]	.....	1.81	+0.17	20.54	23.11	+0.32	.....	+ 706	2,295
	Apr.	1,287	- 302	18,586	16,808[c]	.....	1.67	+0.03	20.57	23.43	+0.32	.....	+ 706	2,295
	May	960	- 629	17,957	17,779[c]	.....	3.19	+1.55	22.12	23.87	+0.44	.....	+ 971	2,560
	June	1,376	- 213	17,744	18,882[c]	.....	1.92	+0.28	22.40	24.37	+0.50	.....	+1,103	2,692
	July	7,850	+6,261	23,005	20,073	.....	5.28	+3.64	26.04	24.91	+0.54	.....	+1,191	2,780
	Aug.	300	-1,289	22,716	20,571	+498	1.49	-0.15	25.89	25.33	+0.42	1,185	+ 927	2,516
	Sep.	2,855	+1,266	23,982	20,741	+170	5.62	+3.98	29.87	25.79	+0.46	370	+1,015	2,604
	Oct.	34	-1,555	22,427	20,975	+234	0.23	-1.41	28.46	26.17	+0.38	615	+ 838	2,427
	Nov.	302	-1,287	21,140	21,272	+297	1.72	+0.08	28.54	26.52	+0.38	780	+ 838	2,427
	Dec.	876	- 713	20,427	.....	+281	0.77	-0.87	27.67	.....	+0.22	1,278	+ 485	2,074
1940	Jan.	578	-1,011	4,784	5,943	- 851	0.48	-1.16	18.97	19.57	-0.22	3,870	- 485	1,104
	Feb.	1,038	- 551	4,233	5,479	- 464	0.21	-1.43	17.54	19.20	-0.37	1,257	- 816	773
	Mar.	292	-1,297	2,936	5,057	- 422	0.00	-1.64	15.90	18.89	-0.31	1,359	- 684	905
	Apr.	871	- 718	2,218	4,263[c]	.....	0.88	-0.76	15.14	18.53	-0.36	.....	- 794	795
	May	4,716	+3,127	5,345	3,579[c]	.....	4.23	+2.59	17.73	18.22	-0.31	.....	- 684	905
	June	713	- 876	4,469	2,895[c]	.....	2.25	+0.61	18.34	17.91	-0.31	.....	- 684	905
	July	1,222	- 367	4,102	2,255[c]	.....	1.91	+0.27	18.61	17.62	-0.29	.....	- 640	949
	Aug.	3,566	+1,977	6,079	1,571[c]	.....	3.58	+1.94	20.55	17.31	-0.31	.....	- 684	905
	Sep.	523	-1,066	5,013	931[c]	.....	0.72	-0.92	19.63	17.02	-0.29	.....	- 640	949
	Oct.	.....	.....	.....	.....	.....	0.23[d]	-1.41	18.22	.....	.....	.....	.....	.....
	Nov.	.....	.....	.....	.....	.....	1.28[d]	-0.36	17.86	.....	.....	.....	.....	.....
	Dec.	.....	.....	.....	.....	.....	0.22[d]	-1.42	16.44	.....	.....	.....	.....	.....
1941	Jan.	.....	.....	.....	.....	.....	0.69[d]	-0.95	15.49	.....	.....	.....	.....	.....
	Feb.	.....	.....	.....	.....	.....	0.00[d]	-1.64	13.85	.....	.....	.....	.....	.....
	Mar.	.....	.....	.....		.....	0.22[d]	-1.42	12.43	.....	.....	.....	.....	.....
Totals		127,133	.....	.....	.....	.....	130.83	.....	.....	.....	.....	.....	.....	114,271
Means		1,589	.....	.....	.....	.....	1.64	.....	.....	.....	.....	2,206	.....	.....

[a]Summations are for the end of the month. [b]Arbitrary initial value on February 1, 1934. [c]Average curve extended from data in column (14). [d]Not used in computation of total rainfall or monthly mean.

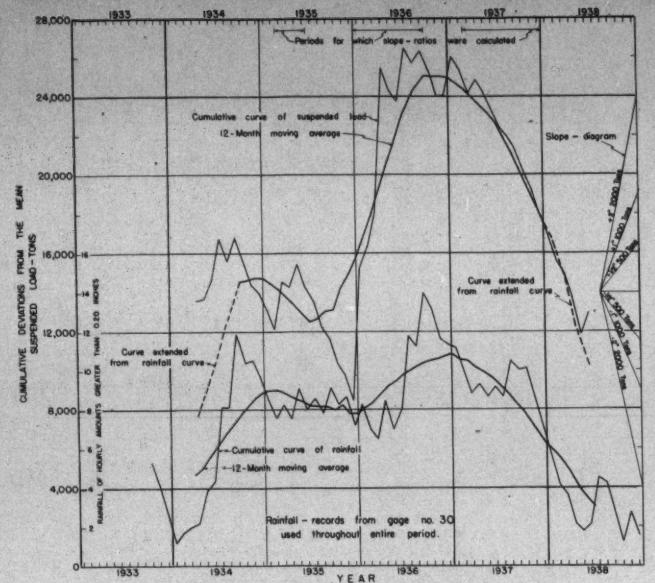
Periods for which slope-ratios were calculated
Cumulative curve of suspended load
12-Month moving average
Slope-diagram
Curve extended from rainfall curve
Curve extended from rainfall curve
Cumulative curve of rainfall
12-Month moving average
Rainfall-records from gage no. 30 used throughout entire period.
CUMULATIVE DEVIATIONS FROM THE MEAN SUSPENDED LOAD-TONS
RAINFALL OF HOURLY AMOUNTS GREATER THAN 0.20 INCHES
YEAR

Fig. 5--Mass-curves of monthly suspended load and rainfall for east fork of Deep River

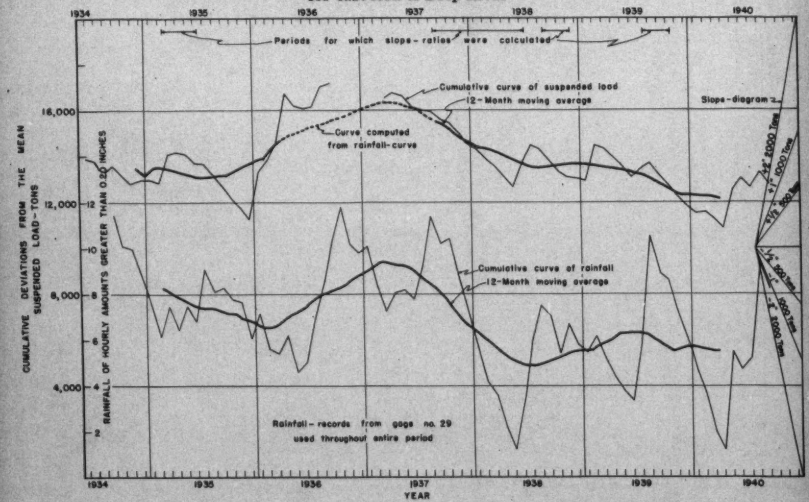
Periods for which slope-ratios were calculated
Cumulative curve of suspended load
12-Month moving average
Slope-diagram
Curve computed from rainfall-curve
Cumulative curve of rainfall
12-Month moving average
Rainfall-records from gage no. 29 used throughout entire period
CUMULATIVE DEVIATIONS FROM THE MEAN SUSPENDED LOAD-TONS
RAINFALL OF HOURLY AMOUNTS GREATER THAN 0.20 INCHES
YEAR

Fig. 6--Mass-curves of monthly suspended load and rainfall for Muddy Creek

Table 2--Summary of slope-ratios for three Piedmont streams

Stream	Water-shed-area	Average slope-ratio	Average slope-ratio per square mile
	sq mi	Tons deviation per inch deviation of rainfall	
Muddy Creek	16.2	633	39.1
West Fork Deep River	32.1	2,206	68.7
East Fork Deep River	13.9	2,465	177.5

for the individual months differ considerably from the observed loads in Column (3); however, the total loads for the entire period of record agree to within ten per cent.

By a procedure similar to that illustrated in Table 1 the data for East Fork of Deep River were analyzed and are summarized in Figure 5. Here, as in the case of West Fork of Deep River, the average mass-curve of hourly rains of 0.20 inch or more appears to be related to the average mass-curve of suspended load. By extending the mass-curve of rainfall for a period of six months at each end and applying an average slope-ratio (Table 2), the computed load for the entire period of record (April, 1934, to June, 1938) was found to be 64,601 tons as compared to an observed load of 67,923 tons, or a difference of five per cent.

An example of the usefulness of the mass-curve in estimating loads for periods during which actual observations are missing is illustrated by the data on Muddy Creek, a tributary to Deep River (Fig. 3). Suspended-load observations were made on this stream from June 1, 1934, to September 30, 1936, and from March 1, 1937, to September 30, 1940. No observations were made during the five-month period between October 1, 1936, and March 1, 1937; however, during the entire period of record rainfall-data for gage No. 29 (Fig. 3) were collected. From these various data a mass-curve of rainfall and mass-curves of suspended load for the two periods of record were computed (Fig. 6). In order to estimate the suspended load transported during the five-month period when observations were not made, the average slope-ratio was calculated for those periods indicated in Figure 6. Using this average slope-ratio in conjunction with the mass-curve of rainfall, the computed deviations of load for the period of missing records were obtained by the procedure illustrated in Column (14) of Table 1.

For a visual observation of the trend of these computed values, the mass-curve of suspended load for the period July, 1934, to September, 1936, was extended to March, 1937 (when the second portion of the mass-curve of suspended load started), by plotting the calculated deviations of load. Since the values used in plotting the two original portions of the load-curve were purely arbitrary, the relative vertical position of two portions could be changed at will; thus, to make the final curve continuous, the second portion of the load-curve was shifted vertically until the ends of the computed and actual curves coincided. The loads for the five-month period of missing records were computed by the method illustrated in Column (15) of Table 1.

Conclusions--These various illustrative examples indicate that there probably is a definite relationship between the suspended load of Piedmont streams and the total rainfall in excess of a certain intensity. In the three streams under consideration an hourly amount of 0.20 inch or greater was considered adequate to describe the rainfall-intensity below which no appreciable amount of suspended matter would reach the drainage-stream. This value of 0.20 inch probably is only approximate and also probably is not constant throughout the year; however, for practical purposes, most rains were either much greater or much less than this value, and any borderline rains were of little consequence when 12-month moving averages are used.

The best choice of designating intensity of rainfall will no doubt vary with different streams. In smaller streams, for instance, it may be necessary to base the mass-curve of rainfall on rains of one-half-hour or even one-quarter-hour amounts instead of hourly amounts as used in the above examples. Smaller periods of suspended-load totals also may be advantageous in certain cases.

For a particular stream the values of the slope-ratios for the individual months were found to differ to some extent, depending on whether slope of the mass-curves were negative or positive; however, for the period of record an average ratio based on all individual values was found to give results of sufficient accuracy for most practical problems.

In the extrapolation of certain data by means of mass-curves and an average slope-ratio, consideration should be given to whether those factors that control the supply of material to the stream, such as land-use and methods of cultivation, will remain essentially unchanged from that existing during the period of sampling.

The average values of the slope-ratio, when reduced to a per-square-mile-of-watershed basis, give a relative index of the seriousness of erosion on the various watersheds, especially as far as the effect on the suspended load of the drainage-stream is concerned. For example, the slope-ratios per square mile of watershed for the East and West Forks of Deep River and Muddy Creek are shown in Table 2, and indicate that of the three streams, the East Fork of Deep River is by far the largest contributor to the suspended load of Deep River.

From a practical standpoint, the application of mass-curves to the analysis of suspended-load problems probably is limited to small watersheds where the effect of rainfall-distribution is relatively unimportant.

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Washington, D. C.

DISCUSSION

S. K. LOVE (U. S. Geological Survey, Washington, D. C.)--The close agreement of values of loads of suspended matter computed from mass-curves with the actual determined loads in small streams near High Point, North Carolina, over a period of several years suggests that the mass-curve method may be useful in evaluating sediment-loads in streams having small drainage-areas, provided that the data on which the computations are based cover a sufficiently long period of time, and provided that the data reliably represent the natural phenomena.

Discharge-data based on daily or twice-daily gage-height readings supplemented by occasional current-meter measurements, and sediment-concentrations based on one or two samples per day are inadequate for the computation of reliable values of runoff and suspended loads for small drainage-areas during flood-periods. The discharge and sediment-load data used by Mr. JOHNSON, which were obtained by the Geological Survey, were based on discharge-records determined from recording gages and frequent current-meter measurements, and on sediment-concentrations determined on a large number of samples collected at frequent intervals during each flood-period. These data are believed to represent reliably discharge- and sediment-loads for the streams for which computations of mass-curves have been made.

The necessity for intensive sampling of suspended sediment in small streams during storm-periods is generally recognized by those engaged in the measurement of sediment-loads. The records of annual loads are no better than the records of storm-loads. It has been shown [see 1 of "References" at end of discussion] that almost the entire annual sediment-load in many small streams is carried during a period of only a few days. Seventy per cent of the total loads of suspended matter measured in the West Fork of Deep River near High Point during the 15-month period ending June 30, 1935, was carried by the stream in 18 days. Eighty per cent of the total loads measured in the East Fork of Deep River during the same period was carried in 20 days.

The necessity for collecting frequent samples during storm-periods is also shown by the wide difference in the results of daily sediment-loads computed from sediment-concentrations in samples collected at different times during a storm-rise on Coon Creek at Coon Valley, Wisconsin, on September 10, 1938. Most of the runoff at the gaging-station occurred between midnight on September 9 and midnight on September 10, with the largest part concentrated between $2^h\ 00^m$ and $8^h\ 00^m$ a.m. on September 10. Sediment-concentrations changed rapidly, particularly during the rising stage. The concentration was 3,670 parts per million at $12^h\ 05^m$ a.m., 9,500 parts per

million at $12^h\ 30^m$ a.m., and reached a maximum of 31,400 parts per million at $1^h\ 00^m$ a.m. The discharge also increased rapidly during this period but did not reach a maximum until an hour and a half after the time of maximum sediment-concentration.

If the sediment-load for September 10 had been computed on the basis of the sediment-concentration at $12^h\ 05^m$ a.m. and the mean daily discharge, the load would have been 6,760 tons for the day. If the load had been computed on the basis of the sediment-concentration at $1^h\ 00^m$ a.m. and the mean daily discharge, the load would have been 57,800 tons for the day. The actual load, based on the sediment concentration in 24 sets of samples and the instantaneous discharge at each sampling-period, amounted to 16,100 tons. This illustration is not unique as similar conditions are found in other small streams. They show that for small streams the most important requirement for the computation of suspended loads is that enough samples shall be taken at the right times, especially during rising stages.

Extrapolated values of suspended sediment-loads beyond periods of actual observation, and interpolated values for periods of missing record would be of most use for those small streams in which the bed-load is only a small part of the total load. Although appreciable quantities of coarse sediment were observed in sediment-traps on streams on the High Point Project, there is reason to believe that the bed-load was only a small proportion of the total sediment-load carried by the streams. Mechanical analyses [2] of 24 samples of suspended matter collected from West Fork of Deep River during several storm-periods in the spring of 1935 indicate that the suspended matter carried in this stream consisted largely of fine material. From about 30 to 70 per cent of the material in these samples consisted of particles less than five microns in diameter, and from about 55 to 90 per cent consisted of particles less than 20 microns in diameter.

It will be of interest to determine the applicability of the mass-curve method of computing suspended loads to small drainage-areas in other parts of the country for which data are available similar to those used in the High Point computations.

References

[1] S. K. LOVE, Suspended matter in several small streams, Trans. Amer. Geophys. Union 1936, pp. 447-452.
[2] Unpublished data in files of the Geological Survey.

R. S. GOODRIDGE and FRANK GRABSKI (Soil Conservation Service, Washington, D. C.; communicated)--The circumspect attitude of the careful hydrologist, taken by Mr. JOHNSON with respect to the factors controlling the supply of sediment to the stream-system, is gratifying, especially since much experimentation in the various derivatives of precipitation is in progress.

Whether the fluctuations of both short-term and long-term hydrologic records have persistency in the trend to excess or deficiency is not necessarily the point the hydrologist is immediately concerned with. What is important is that all of the readily available data pertinent to the controlling factors should be employed in attempting an evaluation.

The object of this discussion is to elaborate somewhat on the long-term evaluation of the mean annual precipitation of the Greensboro and Greenville regions as shown on Figure 1 of the author.

Considerable work has been done on the precipitation-history for the Piedmont Region in conjunction with the flood-surveys of the Roanoke and the Pee Dee River watersheds. The background of these studies made available much information on the general characteristics of the rainstorms of the Southeastern States which are pertinent to the immediate areas about Greenville and Greensboro of South and North Carolina. A map (see Fig. C) shows the portions of the Southeastern States with the locations of the precipitation-stations used in the studies.

The outstanding feature of the region as a whole was the tendency of the indices of precipitation at stations in the Upper Pee Dee River Watershed above Rockingham, North Carolina, to be in agreement, whereas, those to the southwest toward Spartanburg and Greenville gave evidence of rather abrupt differences from those of the Upper Pee Dee. This infers that storms from the Tropical Atlantic moisture-source region have paths which generally pass over the Pee Dee but are turned toward the Northeast by the Appalachian Mountains. Those storms may often come in over Charleston, South Carolina. The storms which bear to the west and come in over Savannah, Georgia, may often be projected over Augusta, Georgia, and Aiken, South Carolina, to Greenville

and Spartanburg, South Carolina, and leave high amounts of precipitation before being deflected northeasterly over the Pee Dee. As a consequence of the above, which had been indicated by a study of the regional records and further confirmed by consultation with the Hydro-meteorological Division of the United States Weather Bureau, a selection of the available precipitation-records was made for study of the long-term (90 years or more) fluctuations.

For the Greenville Region the following records beginning in years indicated were used in the order named with Savannah as the control-record: Savannah (Georgia), 1840; Aiken (South Carolina), 1855; Augusta (Georgia), 1869; Spartanburg (South Carolina), 1875; Greenville, 1890; Longshore, 1888; Simpsonville, 1890; Clemson College, 1892; Greenwood, 1894; Liberty, 1900; Saluda, 1902; Laurens, 1902; and Pelzer, 1905. The indices as percentages of the 90-year average (1852-1941) are developed from the control to the right in the order given above. The arithmetic aver-

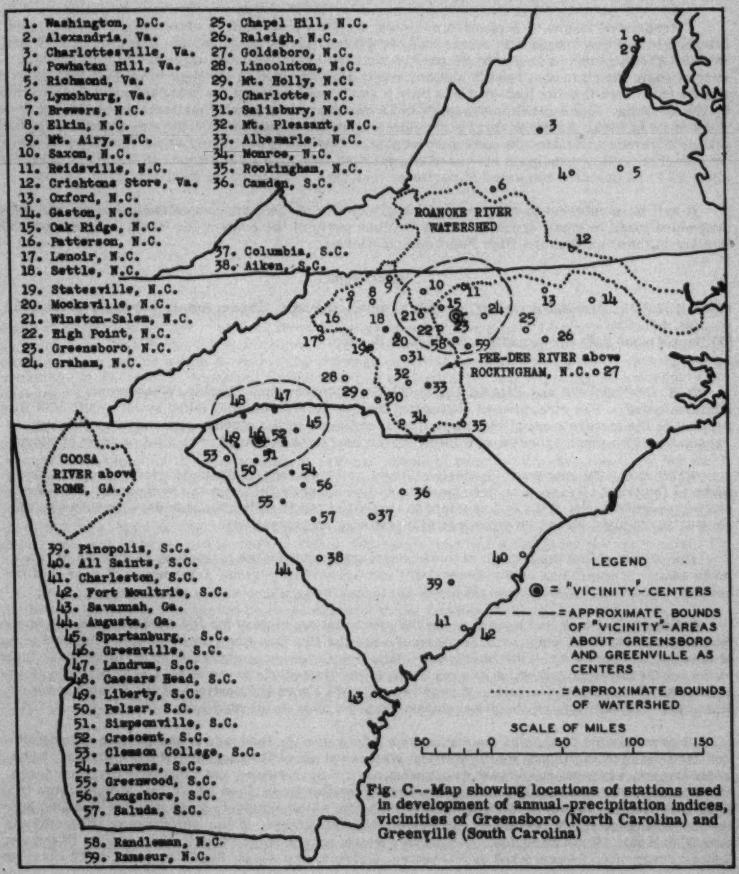


Fig. C--Map showing locations of stations used in development of annual-precipitation indices, vicinities of Greensboro (North Carolina) and Greenville (South Carolina)

age of the station-records in per cent by years constitutes the indices to be used for any missing years of record. It is obvious that this procedure yields indices which are stronger in the later years than in the earlier years: however, since all the available precipitation-records have been used, the indices are the best that can be had from that approach. In the future additional criteria may be utilized.

The indices developed for the Greenville Region were used for the years preceding the establishment of the station at Greenville in the development of the indices for the vicinity of Greenville. The stations used in the study of the vicinity were as follows: Greenville, 1890; Spartanburg, 1875; Simpsonville, 1890; Liberty, 1900; Pelzer, 1905; Landrum, 1915; Caesar's Head, 1925; and Crescent, 1927. The area represented by the vicinity stations embraces approximately 1,400 square miles.

The agreement between the trends shown for the Region and for the vicinity of Greenville are reasonably close. The use of both sets for the Region and vicinity serves a more rigorous examination of the relative degree of agreement between the two and thereby aids in the evaluation of both. The first makes the second possible by establishing a point of beginning. The second strengthens the evaluation of the fluctuations about an individual station, as Greenville, as the more removed stations are excluded from exercising their weight in influencing the fluctuations of the period for which records are available. The added stations of the study of the vicinity serve to diminish the influence of fortuitous incidents which might be incorporated in a record at an individual point. The trend of Figure A is to indicate that heavier than average precipitation was experienced by the Region and the vicinity of Greenville in the period 1840 to 1890.

An inspection of Figure A shows that the deviations from the 90-year average (1852-1941) are cumulated to 139 points through the year 1889 in 38 years, an average of + 3.66 points a year. By construction, the 139 points will be lost during the remaining 52 years of the period, the period of record at Greenville. The average for the 52 years is - 2.67 points per year. A straight line may be drawn for this average as is shown on Fig. A. The lower of the two such straight lines is that for the cumulated percentage points or indices; the upper is the cumulated deviations in inches for the point-record at Greenville. The author's corresponding line appears on Figure 1 as the 20-inch line which was used as the base for the cumulated deviations of the Greenville precipitation in inches for the record-period 1890 through 1941, designated by the author as the "mean annual rainfall" with an evaluation of 51.46 inches. The 90-year (1852-1941) indicated average precipitation for the vicinity of Greenville, developed in this discussion, is 52.87 inches, an increase of 1.41 inches or 2.67 per cent. Some hydrologists have shown hesitancy in interesting themselves in such a small percentage; however, they had not perceived of the concept of its significance in terms of excess and deficiency. This can be developed further.

The "normal" regime of a region is conditioned by its proximity to sources of moisture. In the Piedmont about Greenville, with an average precipitation of about 52 inches, the range of precipitation within the "below-average" and "above-average" quartiles of the amounts varies from 46 to 57 inches, or between 87 and 108 per cent. This range is about 11 inches or an average deviation-boundary or limit of 5.5 inches. A 90-year increase of 1.41 inches, then, amounts to a 25 per cent heavier precipitation than in the apparent regime ascertained from the period of record. Emphasis might be made by recalling a simple adage to the effect that six inches is not much in a mile but add it to the end of your nose and it means something. This analogy is purposefully exaggerated to orient the reader to the concept of precipitation-excess and precipitation-deficiency in correlation with hydrologic events.

A similar study was made of the precipitation at Greensboro, North Carolina. This was considerably more involved with respect to the manner of developing the indices for the period preceding the establishment at Greensboro, 1892.

Greensboro, North Carolina, lies approximately 225 miles north of Charleston, South Carolina, and about 240 miles southeast of Washington, D. C. All are stations with long-term records of precipitation. It was considered that Greensboro would be in a transition-area between the two and that the long distances would be, in effect, shortened by the use of stations somewhat closer in the studies of the vicinity which were developed from the centers of Washington and Charleston toward Greensboro. The relative positions of the stations are shown on Figure C.

Accordingly, the Washington to Pee Dee indices-control was developed from the following records: Washington, D. C., 1832; Powhatan Hill, Virginia, 1850; Alexandria, Virginia, 1853; Richmond, Virginia, 1851; Lynchburg, Virginia, 1871; and Charlottesville, Virginia, 1874, as the initial year of the record. The Charleston, South Carolina - Pee Dee indices-control was developed

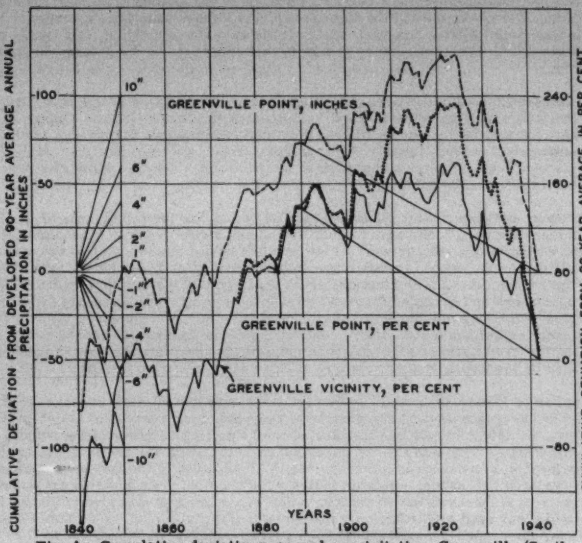


Fig. A--Cumulative deviations, annual precipitation, Greenville (South Carolina) and vicinity, calculated from average for 90-year period, 1852-1941

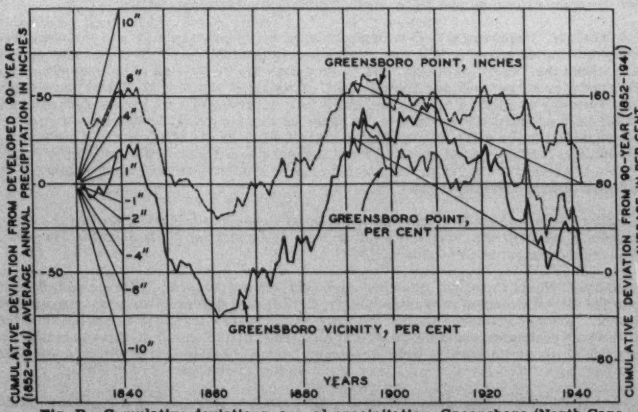


Fig. B--Cumulative deviations, annual precipitation, Greensboro (North Carolina) and vicinity, calculated from average for 90-year period, 1852-1941

from the following: Charleston, South Carolina, 1832; Pinopolis, South Carolina, 1846; Aiken, South Carolina, 1855; Fort Moultrie, South Carolina, 1843; All Saints, South Carolina, 1851; and Columbia, South Carolina, 1873.

The above developed indices were both used as the controls for the regional study of the Pee Dee River comprising the following: Camden, South Carolina, 1850; Crichton's Store, Virginia, 1854; Gaston, North Carolina, 1857; Chapel Hill, North Carolina, 1856; Goldsboro, North Carolina, 1867; Raleigh, North Carolina, 1867, Oxford, North Carolina, 1867; Statesville, North Carolina, 1867; Lenoir, North Carolina, 1872; Charlotte, North Carolina, 1873; Mount Holly, North Carolina, 1886; and Lincolnton, North Carolina, 1885.

As was previously discussed under the study for the vicinity of Greenville, South Carolina, the regional indices were further focused on the Pee Dee River Watershed by recalculating the regional study with the major controls superseded by local records when available. The watershed-study comprised the following stations, all in North Carolina: Lenoir, 1872; Charlotte, 1873; Statesville, 1867; Salisbury, 1888; Mount Airy, 1889; Mount Holly, 1886; Mount Pleasant, 1887; Monroe, 1888; Greensboro, 1892; Rockingham, 1893; Oak Ridge, 1891; Mocksville, 1893; Winston-Salem, 1896; Settle, 1896; Brewers, 1897; Patterson, 1897; Randleman, 1905; Albemarle, 1911; Elkin, 1913; and High Point, 1921.

The indices from the watershed-study were further examined for focusing on the immediate vicinity of Greensboro, an area of about 2,000 square miles or with a radius of about 25 miles. The following stations were used: Greensboro, 1892; Ramseur, 1890; Oak Ridge, 1891; Saxon, 1892; Winston- Salem, 1896; Reidsville, 1902; Graham, 1902; Randleman, 1905; and High Point, 1921.

In all, five studies were made to get to the supporting indices for the evaluation of the Greensboro record-period precipitation in terms of the longer records of the Region. This work developed smoothly and in stride from the previous studies for the Susquehanna River Watershed and the Youghiogheny River, Pennsylvania, the Coosa River, Georgia, and the Roanoke River, Virginia. The indices for the vicinity of Greensboro were in good agreement with those of the Pee Dee River Watershed above Rockingham.

The Greensboro-vicinity and "point"-record indices are shown on Figure B in terms of the cumulated deviations in a manner similar to the diagram made for the Greensville. The developed long-term average precipitation for Greensboro, developed from the vicinity-study, was 47.71 inches for the 90-year period (1852-1941) while that shown on Figure 1 of the author was 46.54 for the 50-year period of record, 1892-1941. The difference is 1.17 inches per year. Similarly as for the Greenville, the range of the "above-average" and "below-average" quartiles are respectively, 108 and 89 per cent. The equivalent in inches are 51.5 and 42.5 inches, a range of nine inches or an average deviation of 4.5 inches. The increase of the record-period average over the 90-year average of 1.17 inches is equal to 26 per cent of average regime, though the increment of increase is but 2.45 per cent of the 90-year average. The upper diagonal line of Figure B corresponds to the 10-inch line of Figure 1 of the author, the assumed base-line for the deviations.

A satisfying observation is evident by noting the trend of the "point" cumulative deviations with the trend of the vicinity cumulative deviations. This is the tendency of the point-line of the cumulative deviation in per cent to take a position below the vicinity-line at Greensboro and above at Greenville. This tendency is in accord with the trends shown by the cumulative-deviation curves for the Roanoke and the Coosa River watersheds. The principal features of the curves are set forth in the following Table 1.

From Table 1 there is evidence of a gradient in geographical phase-change in a southwesterly direction from the Roanoke towards the Coosa. Accordingly it follows that cumulative deviations of the precipitation-measurements at Greenville and Greensboro will tend to be asymmetrical to the cumulative deviations of the group which form the "vicinity" if there is some dominance of either the point or member stations of the group. The "point," Greenville, tends to be "westerly" in its group by appearing to peak rather sharply toward 1939 while the "vicinity"-deviation curve shows the dominance of the relatively long record at Spartanburg with a trend opposite to that of the curve for the Coosa. Similarly, Greensboro tends to be centrally located in its group with stations of the "vicinity" tending to dominate with a western influence throwing the "vicinity"-curve higher than the "point"-curve.

Table 1

Item	Hydrologic regions			
	Coosa River Watershed, Rome, Georgia	Greenville vicinity, South Carolina	Greensboro vicinity, North Carolina	Roanoke River Watershed, Roanoke Rapids, Virginia
Peak-year, cumulative deviations	1939	1924	1909	1909
Minimum year, cumulative deviations	1891	1862	1861	1861
No. years precipitation - excess trend	48	62	48	48
Approximate longitude in degrees	85	82 - 30	80	80
Geographical phase-change or lag in years	30	15	0	0
Percentage of years of precipitation-excess above 90-year period	53	69	53	53

From the foregoing it may be concluded that hydrologists and the engineers who use their conclusions can be reasonably sure that heavier-than-"average" precipitation was experienced by the areas of the Southeastern States during the period 1850 to 1890. It follows that hydrologic conclusions may be strengthened by an examination of all of the data available which is pertinent to the immediate investigations and studies. In this manner the engineer may be guided in choosing the magnitude and sign of the factor of safety which is to be considered in the design of public works.

DISTRIBUTION OF SUSPENDED SEDIMENT IN A NATURAL STREAM

Alvin G. Anderson

Introduction--The sediment-load of a natural stream may be considered to be made up of two parts, the wash load and the bed-materials load [see 1 of "References" at end of paper]. The wash load is the fine material washed into and through the reach under consideration by storm-runoff. The bed-materials load is derived from the bed of the stream and may be transported either by rolling along the bed or in suspension. The various particles moving in suspension come into contact with the bed with a frequency depending on their size.

The distribution of the suspended particles in the body of the flow is dependent upon the equilibrium between the random vertical-velocity fluctuations and the force of gravity. The steps in the development of the theory and its application to suspended sediment have been clearly presented by various authors [2,3,4] and need not be repeated here. The theory recently has been tested by VANONI [5] with data obtained from laboratory flume-experiments in which measurements were made of the vertical distribution of sediment introduced into the flowing water. The equation, used by VANONI but first introduced by ROUSE [2], describing this vertical distribution is

$$(C/C_a) = [(D-y)/y][a/(D-a)]^z = H^z \qquad (1)$$

where $z = w/(k\sqrt{\tau_o/\rho})$.

Equation (1) gives the relative sediment-distribution in a two-dimensional flow for a given particle size having a settling velocity, w, in the still fluid. In this equation C is the concentration at any point a distance, y, above the bottom and C_a is the reference-concentration at some arbitrary distance, a, above the bottom; k is the universal constant for turbulent exchange and has an average value of 0.4 for clear fluids; and $\sqrt{\tau_o/\rho}$ is the friction-velocity which in a two-dimensional open channel is equal to $\sqrt{gDS}$ where S is the slope of the channel and D is the depth.

Observations--In connection with studies pertaining to the measurement of the sediment-load of natural streams, the Sedimentation Division of the Soil Conservation Service has collected a large number of suspended-load samples, among which have been sets of samples taken in single verticals. The purpose of these samples has been to determine the vertical and horizontal distribution of suspended sediment in order to calculate the total suspended load. Most of the samples have been collected at a section of the Enoree River where the reach is quite regular and fairly straight. At the point of collection the river is about 50 feet wide and has a sand-bed and almost vertical banks.

The slope of the stream was computed from the records of two recording-gages located 1,332 feet apart at the upper and lower ends of the reach.

The sampling-apparatus consisted of a number of samplers attached at regular intervals to the support which in turn was suspended on a sounding cable from a gaging-car. The sampler used was a tube of the type developed at this laboratory [6], which had been calibrated to measure the velocity simultaneously with the collection of the samples. The samples, collected in pint milk bottles, were analyzed at the Greenville Laboratory of the Sedimentation Division. Mechanical analysis was made only of that fraction of the suspended load having grain-sizes greater than 0.061 mm, the size previously determined for this location as the practical dividing size between that part of the sediment which is uniformly distributed in the vertical and the part with varying concentration. The coarse fraction was mounted loose for projection by a microprojector. The grains within each grade size were counted and converted to concentration by weight. The results of the analysis and the location of the sampling-points are given for a number of verticals in Table 1. Mechanical-analysis curves for samples of the stream-bed already have been published [1].

Table 1--Suspended-matter concentrations in Enoree River

Sample No.	Distance above bed, ft	H $\frac{D-y}{y}\left(\frac{a}{D-a}\right)$	Velocity, ft/sec	Concentration, ppm by weight for grade-size, mm						
				0.074-0.124	0.124-0.175	0.175-0.246	0.246-0.351	0.351-0.495	0.495-0.701	0.701-0.991
E(2-19-40)	0.15	0.660	1.87	2.4	8.5	45.3	67.1	130.9	82.2	.....
SN - 2:40	0.45	0.206	2.30	2.3	3.8	16.8	43.8	95.4	88.7	.....
	0.75	0.1155	2.15	1.4	5.5	16.8	32.6	65.3	58.5	.....
	1.35	0.0552	2.90	1.5	4.8	13.1	26.4	38.1	30.5	.....
	1.95	0.0319	2.85	2.2	5.3	13.6	17.8	27.5	20.4	.....
	2.55	0.0196	3.25	7.1	10.3	15.5	13.5	10.3	10.5	.....
	3.15	0.0120	3.63	2.8	3.9	9.3	10.0	10.2	7.5	.....
E(2-19-40)	0.15	0.619	2.08	0.7	2.1	3.9	13.7	26.6	29.2	.....
SN - 16:25	0.45	0.193	2.05	1.0	2.7	5.8	10.9	20.4	15.7	.....
	0.75	0.1075	1.90	0.8	3.0	6.3	7.5	18.9	22.4	.....
	1.35	0.0506	2.55	0.8	1.4	3.4	6.2	11.2	14.1	.....
	1.95	0.0288	2.33	0.6	0.9	3.2	5.7	8.8	6.2	.....
	2.55	0.0172	2.75	0.6	2.1	3.6	4.5	8.0	4.9	.....
	3.15	0.0100	2.72	1.3	2.3	4.2	3.6	4.5	2.2	.....
	3.75	0.00517	2.10	1.0	2.3	4.2	2.4	1.3	0.7	.....
E(2-19-40)	0.15	0.551	1.85	3.0	5.0	16.9	61.1	160.0	160.0	.....
SN - 17:00	0.45	0.170	1.85	0.9	1.9	9.8	27.6	58.2	57.5	.....
	0.75	0.094	1.87	1.1	2.9	7.7	15.7	35.8	33.2	.....
	1.35	0.0432	2.77	0.8	3.8	6.6	13.6	27.0	13.5	.....
	1.95	0.0236	2.65	0.6	1.3	6.1	10.4	9.1	14.1	.....
	2.55	0.0133	2.96	0.9	2.1	2.2	10.4	13.1	6.2	.....
	3.15	0.0068	3.38	1.2	1.9	4.1	4.4	4.9	0.7	.....
	3.75	0.00246	2.77	0.5	2.0	1.9	3.6	3.2	2.8	.....
E(2-19-40)	0.15	0.680	0.59	0.5	3.0	8.7	22.3	25.5	46.4	36.3
SN - 17:07	0.45	0.213	1.59	1.4	4.0	9.0	15.6	21.2	21.8	10.9
	0.75	0.120	1.52	1.0	2.9	9.0	11.0	16.4	16.5	4.0
	1.95	0.0335	2.04	0.5	1.4	3.7	3.9	3.1	4.4	2.8
	2.55	0.0208	2.40	0.7	2.0	4.8	5.5	5.4	6.8	7.2
	3.15	0.0130	2.67	0.6	1.3	3.9	5.2	7.7	9.0	.....
	3.75	0.0076	2.10	0.3	2.2	4.1	5.7	6.4	.....	.....
E(7-7-41)	0.15	0.483	0.79	3.2	5.8	6.4	7.4	8.9	.....	.....
SN - 15:20	0.45	0.147	1.11	2.2	4.3	7.9	6.0	7.2	.....	.....
	0.75	0.081	1.26	1.6	2.8	4.0	6.1	4.9	.....	.....
	1.35	0.0355	1.77	1.1	2.1	2.7	2.2	2.8	.....	.....
	1.95	0.0183	1.62	2.3	3.5	4.8	1.8	1.7	.....	.....
	2.55	0.0092	1.74	2.5	4.2	2.4	1.9	0.5	.....	.....
	3.45	0.0015	1.70	2.1	2.3	2.5	0.7	0.4	.....	.....
E(7-7-41)	0.15	0.388	0.90	1.4	6.7	15.8	31.4	39.0	21.7	.....
SN - 16:07	0.45	0.1155	2.00	1.1	2.5	4.0	11.4	19.1	11.3	.....
	0.75	0.0612	1.89	3.3	5.9	8.5	10.8	7.6	12.2	.....
	1.35	0.0249	2.48	1.9	2.7	2.8	4.4	2.2	3.3	.....
	1.95	0.0110	2.40	1.8	2.8	3.2	4.3	2.1	0.5	.....
	2.55	0.0036	1.76	1.4	1.9	1.6	2.3	1.4	.....	.....

Application of theoretical equation--In order to test the applicability of the theoretical equation to field-data, an analysis was made of the data presented in Table 1 in a manner similar to that followed by VANONI [5]. A preliminary plot was made on logarithmic paper of the concentration in each grade-size against the distribution-function H. In the computation by equation (1) of H (a/D) = 0.02. A straight line was fitted to these points and the value of C_a was taken as the concentration where the line intersected the value of H equal to unity. The slope of this line is equal to the exponent z_1 in the equation $(C/C_a) = H^{z_1}$, where z_1 in general differs from z and is referred to as the empirical exponent. This operation was carried out for each grade size in each vertical and the value of C_a and z_1 tabulated in Table 2. In Figure 1 the data for a typical vertical are plotted to show the variation of the relative concentration with the distribution-function H. These data are also plotted in Figure 2 (using the value of z_1 as determined for each grade-size in Fig. 1) to illustrate the variation of concentration with depth. The curves in Figure 2 represent the equation, $(C/C_a) = H^{z_1}$, for values of z_1, determined for each grade-size in Figure 1. The theoretical value of the exponent, z, also tabulated in Table 2, was computed from the equation $z = w/(k\sqrt{gDS})$, using as the fall-velocity, the fall-velocity of a sphere whose diameter was equal to the geometric mean of the grade considered. In this computation the universal cónstant, k, was assumed to be equal to 0.4 because of the lack of correlation in the measured velocity-profiles.

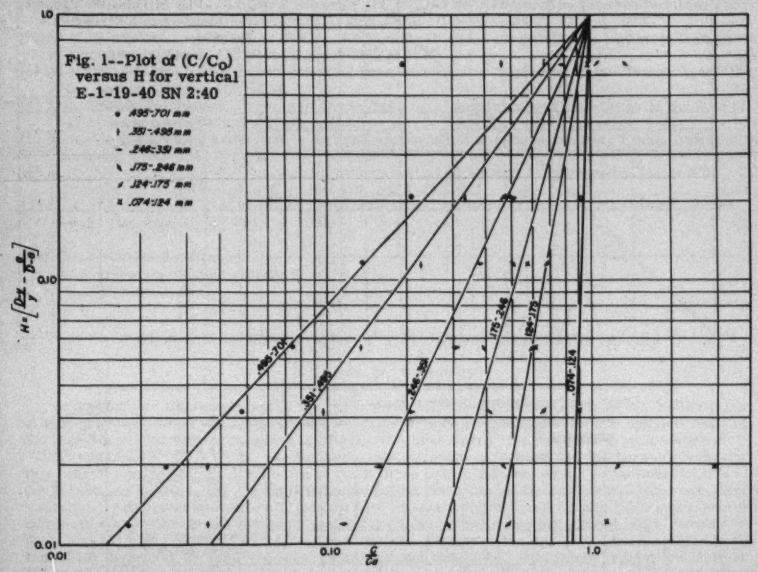
Table 2--Summary of Enoree River observations

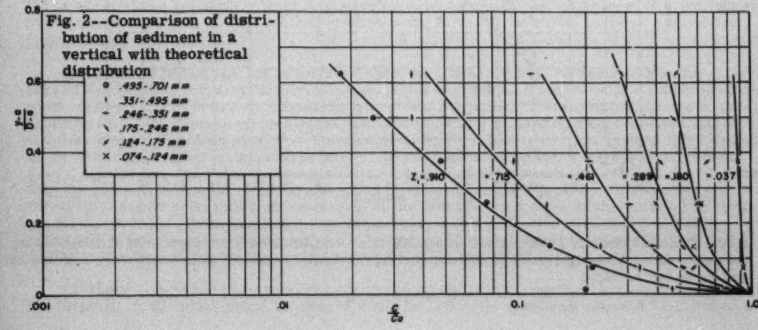
Sample No.	Depth, ft	Slope	Temp., °C	$\sqrt{gDS}$ ft/sec	Grade-size, mm	w, ft/sec	z_1	z	C_a, ppm
E(2-19-40) SN - 2:40	5.0	0.00084	6.2	0.368	0.074-0.124	0.015	0.037	0.100	2.45
					0.124-0.175	0.037	0.180	0.251	8.10
					0.175-0.246	0.066	0.289	0.445	33.00
					0.246-0.351	0.107	0.461	0.722	86.00
					0.351-0.495	0.170	0.715	1.150	285.00
					0.495-0.701	0.256	0.910	1.740	422.00
E(2-19-40) SN - 16:25	4.7	0.000745	7.7	0.334	0.074-0.124	0.015	0.044	0.115	0.88
					0.124-0.175	0.039	0.053	0.292	2.81
					0.175-0.246	0.066	0.150	0.496	6.60
					0.246-0.351	0.108	0.402	0.808	21.50
					0.351-0.495	0.170	0.584	1.270	66.00
					0.495-0.701	0.256	0.706	1.920	56.00
E(2-19-40) SN - 17:00	4.2	0.00074	7.7	0.316	0.074-0.124	0.015	0.107	0.122	1.40
					0.124-0.175	0.039	0.173	0.308	4.40
					0.175-0.246	0.066	0.393	0.525	20.00
					0.246-0.351	0.108	0.500	0.855	67.00
					0.351-0.495	0.170	0.765	1.340	225.00
					0.495-0.701	0.256	0.890	2.020	270.00
E(2-19-40) SN - 17:07	5.15	0.000735	7.7	0.349	0.074-0.124	0.015	0.059	0.110	0.64
					0.124-0.175	0.039	0.197	0.282	3.95
					0.175-0.246	0.066	0.256	0.475	12.00
					0.246-0.351	0.108	0.376	0.773	25.50
					0.351-0.495	0.175	0.490	1.250	42.00
					0.495-0.701	0.259	0.608	1.850	57.00
					0.701-0.991	0.380	0.836	2.720	45.00
E(7-7-40) SN - 15:20	3.7	0.00057	24.0	0.260	0.074-0.124	0.023	0.040	0.217	2.72
					0.124-0.175	0.050	0.101	0.483	5.00
					0.175-0.246	0.088	0.158	0.850	7.10
					0.246-0.351	0.137	0.436	1.320	12.00
					0.351-0.495	0.210	0.670	2.020	26.00
E(7-7-40) SN - 16:07	3.0	0.000565	24.0	0.234	0.074-0.124	0.023	0.094	0.236	2.55
					0.124-0.175	0.050	0.302	0.530	8.60
					0.175-0.246	0.088	0.478	0.927	23.20
					0.246-0.351	0.137	0.547	1.450	50.00
					0.351-0.495	0.210	0.814	2.210	79.00
					0.495-0.701	0.446	1.250	4.680	148.00

The results for all of the data are plotted in Figure 3, wherein the solid line is the equation $(C/C_a) = H^{z_1}$, where z_1 is the measured value of the exponent. This Figure shows that, even though some individual points scatter, the form of the equation fits the points satisfactorily. This fit suggests the possibility that the equation could be used for practical purposes in describing the distribution of suspended particles if an appropriate value of the exponent z_1 is chosen. Probably it is possible to make an estimate of the magnitude of the exponent for a particular section of a stream after a few preliminary samples in several verticals have been analyzed. By this means average values of the exponents for various grade-sizes applicable to this particular section would be obtained.

Study of corresponding values of the theoretical exponent z and the empirical exponent z_1, in Table 2 and Figure 4, shows a wide difference, the theoretical exponent being approximately twice as large as the actual. Some of this difference may be ascribed to errors of observation. The measurement of the slope which appears only as a square root, is subject to the largest error. The assumption of k as being equal to 0.4 may also be in error, but VANONI [5] found that "the presence of sediment tends to decrease k" so that the assumption of k = 0.4 is on the conservative side.

It will be noted in Figure 4 that the difference between the computed and measured values of the exponent increases with the grain-size. The fact that the measured exponent is smaller than the computed value means that the sediment is more uniformly distributed than the theory indi-





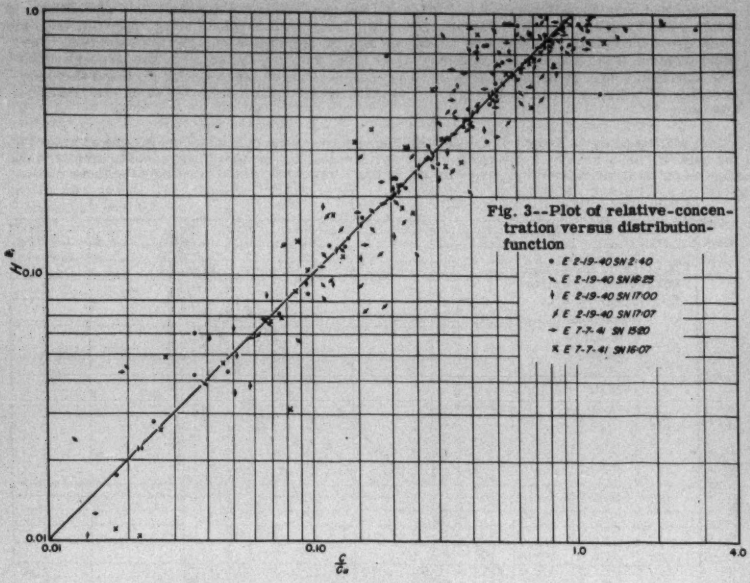


Fig. 3--Plot of relative-concentration versus distribution-function

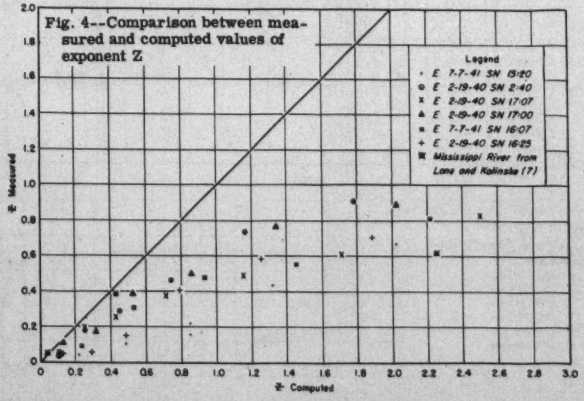


Fig. 4--Comparison between measured and computed values of exponent Z

cates. This may be due to variations in equilibrium-conditions for the suspension of sediment in the reach under investigation or to intense mixing due to the action of eddies that were continually coming to the surface.

The principal results of this analysis are the presentation of data further substantiating the theory of sediment-suspension and the demonstration of the applicability of an equation of this form to the conditions of nature. Although for the Enoree River at the point of sampling the sediment is more uniformly distributed than theory would predict, the shape of the distribution-curves agrees satisfactorily with the theory. Further study into the mechanism of transfer in natural streams is needed so that the value of the exponent may be more accurately predicted.

Acknowledgments--The author is grateful to RICHARD G. GRASSY for his assistance in conducting the laboratory analysis of the various samples.

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STORAGE CONSEQUENCES OF THE GHYBEN-HERZBERG THEORY

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Introduction--Contemplation of the history and functioning of the GHYBEN-HERZBERG lens of stored ground-water which forms the Honolulu Artesian System has led to a consideration of the long-term hydraulic consequences of artificial draft along lines suggested by the work of THEIS and others. This paper is offered as an elementary elaboration of the probable behavior of this lens of ground-water. There are at least three possible forms which a statement of this kind could take, as follows: (A) A simplified, qualitative statement of the probable mechanism indicating the chief factors and their relationship with adequate definition of terms; (B) a more-or-less complete elaboration of the mathematical theory in general terms, but without local, specific data; and (C) a more-or-less complete quantitative solution of the various elements of the problem using measured or assumed local quantities and constants. It is fairly evident that neither (B) or (C) could be set forth without first developing an adequate concept in form (A), and that an attempt to develop (C), without a sound concept in the form (B), would be an undue reliance on empirical procedures.

The problem of storage and storage-changes, in a system operating according to the GHYBEN-HERZBERG theory, involves certain features differing from those of a simple ground-water system, or of the ordinary artesian ground-water system. The consequences are so far-reaching on all the aspects of the system that it is important to develop a correct descriptive understanding of the rudiments, even though data are not in hand to develop a quantitative solution or an elaboration of the mathematical theory. In the Honolulu System, a large body of data on heads, discharges, and rainfall is available for a period of some years past, but the use of these data for any adequate solution of various parts of the problem is hampered in several ways. First, no adequate descriptive understanding of the dynamic functioning of the system has been set forth, second, no mathematical formulation suitable to the peculiarities of the GHYBEN-HERZBERG system or the local aquifer has been developed, and third, there are serious deficiencies in the data with reference to any close analytical treatment.

All these deficiencies are somewhat interrelated and it is recognized that any treatment in the form (B) or (C) which might be offered would be relatively valueless unless it be based on a

descriptive concept in the form (A) which will be generally accepted by competent students. Moreover, in view of the prime local importance of the Honolulu System, any presentation or quantitative treatment which might lead prematurely to quantitative conclusions that were either too optimistic or too pessimistic would be unwise. Bearing these considerations in mind, the writer proposes here to deal with the rudimentary hydrologic behavior of a system of similar character and magnitude to the Honolulu System in respect particularly to fluctuations of intake, draft, and storage-changes over short and long periods. In short this is a description in the form (A). It will be sufficient at some later date to attempt a more specific and more rigorous attack on the problem of the Honolulu System as such.

The GHYBEN-HERZBERG theory--According to the GHYBEN-HERZBERG theory, coastal ground-water, whether of an island or a continent, which is in hydraulic contact with ocean water, tends in an aquifer permeable above and below sea-level to assume an equilibrium-condition in which fresh water extends downward about 40 times as far below sea-level as the fresh water-table extends above sea-level [see 1 of "References" at end of paper]. This is in consequence of the hydrostatic balancing of about 41 vertical units of fresh water against 40 units of salt water, assuming a specific gravity of sea-water which approximates 1.025, or about 41/40 that of fresh water. (A detailed study of the specific gravity of sea-water around Oahu at different times and places resulted in an average value of 1.0261, which corresponds to a GHYBEN-HERZBERG ratio of 38.3 [2]. However, for the present discussion, the round number 40 will be used.) Thus in any restricted area, a vertical column of fresh water would be in hydrostatic, or U-tube equilibrium with the salt water, the U-tube being completed by the salt water beneath, lateral and upward to the free surface of the ocean (Fig. 1). This is wholly correct for static conditions, for two immiscible liquids, or for miscible liquids in an aquifer of low permeability for short periods. Despite the fact that it is not an adequate statement of the conditions of dynamic equilibrium, the GHYBEN-HERZBERG theory may be considered approximately correct and at least an important starting point in the present discussion [3]. Further description will be developed by considering a small, circular island, consisting of permeable rock surrounded by the ocean. Fresh water is supplied by rainfall; retardation of escape by the rock results in building up of a water-table of convex form, whose height above sea-level and whose slope will be determined by the rate of rainfall, and the rate of lateral discharge. The latter is dependent on the permeability of the rock.

It can readily be shown that the upper surface of a water-table caused by such retardation of escape is convex upward, even with uniform rainfall. This convex water-table due to dynamic surcharge tends at once toward the establishing of the larger sub-sea-level part of the bi-convex body of ground-water which is known as the GHYBEN-HERZBERG lens. The relationship between the upper and lower parts of the GHYBEN-HERZBERG lens is essentially a static one, despite the slope of the upper surface. The relationship is analogous to that between the water in a flowing stream and the water in the float-gage pool by which the stage of the flowing stream is recorded. Lacking further recharge from rain, the stream would decline in discharge, but so long as it flows, its rising or falling static level is reflected in the gage-well, with such lag as is fixed by the length and size of the connecting pipe and the area of the free surface of the well.

The elementary concept of the GHYBEN-HERZBERG lens, which is fairly in accord with observed conditions, is that of a bi-convex lens with a fairly sharp edge at the shore margin and with the bottom portion deeply convex to approximately 40 times the convexity of the upper part (Fig. 1). In its simplest form this is a wholly non-artesian system; in the Honolulu Area this is modified to develop artesian conditions underneath a relatively impervious coastal-plain deposit which lies like a patch on and against the pervious aquifer.

GHYBEN-HERZBERG functioning--After such a hydrologic system has been in operation for a long period a condition of approximate equilibrium is set up, the operation of which it is proposed to discuss. Obviously, with continued addition of rainfall to the water-table by infiltration and movement of water down the slope of the water-table toward the periphery of the lens, there must be means of escape to mingle with the sea-water of the ocean. And yet the condition of balance, by which the fresh water remains afloat on the salt water, means that such escape and such mingling is not general or immediate, since this would nullify the static balance. It is essential to the fact of static balance and the integrity of the fresh-water lens, which are matters of observation, that the zone of diffusion or of mixing, or surface of balance, be a boundary across which there is no general movement of fresh water. Taken as a whole this boundary must operate as it would if the two liquids were immiscible. Moreover, in a static system this boundary rises to sea-level at the margin of the land to a line which forms a common junction between air, sea-water, and ground-water. This is a line with only one dimension and hence no water could be transmitted through this line-junction.

In seeking means of continuously passing water through the fresh-water lens and into the ocean, it appears we must seek local nullifications of the enclosing boundary and integrity of the static GHYBEN-HERZBERG lens. These are believed to be chiefly as follows. HUBBERT has suggested in a very brief consideration of the GHYBEN-HERZBERG condition that movement of fresh water seaward causes an opening of the edge of the lens so that fresh water seeps out to the surface in a narrow zone just above sea-level and also emerges from permeable rocks directly into sea-water for some distance offshore and below sea-level [4]. This avenue of escape appears to be the normal and necessary response to the surcharging of the lens by rainfall.

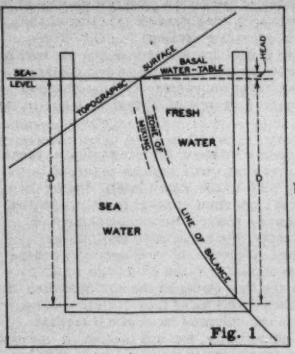


Fig. 1

However, if both the dynamic and static behavior of the GHYBEN-HERZBERG lens be considered it is easy to show that under special conditions subordinate amounts of water may move across the boundary without destroying the general integrity of the lens. For example, in

Fig. 1--Diagram showing ideal cross-section of margin of Ghyben-Herzberg lens in a non-artesian system (In order to show slope of both water-table and line of balance in proper relative values, vertical scale is exaggerated to order of 100:1; hence slope of line of balance is far steeper than in natural lens; fluid balance along line of U-tube follows the equation:

$$D(\text{Sp gr}_{sw}) = (D + H)\ 1$$

$$\text{Ghyben-Herzberg ratio} = (D/H) = 1/(\text{Sp gr}_{sw} - 1)$$

Figure 2, the GHYBEN-HERZBERG balance is expressed by the static equality of water-columns along the line ABCD, and the position of the diffusion-zone is determined by the sum total of hydraulic interconnection from B to A, the head of the water-table at A being determined by more dynamic conditions of supply and depletion. Now, while this balance is maintained, there may nevertheless be a more highly permeable avenue along the course AB′C′D′E′, owing to interconnecting tubes or cracks of larger than common size. It is easily seen that since the deepest part of this avenue is not so deep as the points B and C, the fresh-water head at A is preponderant over any salt-water column that can be established over this avenue and water will move from A and B′ and pass out to mingle with salt water beyond D′. So long as the amount of water passed through this avenue is only a small part of the total currently added at the point A, the general condition of balance can be maintained and the flow of such a deep, submarine spring can be continuous. Both in non-artesian and artesian systems, it seems likely that there are many such places where paths showing hydraulic unbalance permit the seaward flow of considerable amounts of water without changing the prevailing static balance which determines the form and dimensions of the lens.

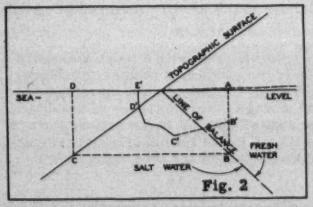


Fig. 2

Fig. 2--Diagram showing margin of Ghyben-Herzberg lens (Line ABCD is line representing controlling U-tube balance; a column of fresh water of height AB balances a column of sea water of height CD; however, weight of a column of fresh water of vertical height A to C′ is greater than that of a column of sea water of vertical height C′ to E′; hence, along this line water will move from B′ to C′ to D′ if somewhat isolated permeable avenues exist)

Moreover, in any complex system involving both large and small openings, either a natural system or a municipal distribution-system, the differences between friction-heads in two adjacent pipes of different size or flow-conditions or both, are such that great variation, or even reversal of cross-flow along a line of constant static potential can take place. Ebb and flow of the tides must in all GHYBEN-HERZBERG systems furnish the primary cause of very complex changes in

rate and direction of water-movement, especially near the boundary, and it seems inevitable that in the net result this must cause water to move from the fresh lens to the ocean across the diffusion-zone, despite the impossibility of such movement taking place in a strictly static system.

Growth and shrinkage of GHYBEN-HERZBERG lens--The upper surface of the lens or water-table is continuously fluctuating in elevation because of daily, seasonal, and cyclical variations in rainfall. Many of these variations are slight in amount and of short period and are in part pulsatory due to effects transmitted from adjacent areas or the tides of the ocean. Others may be of several years or decades duration and amount to several feet, or a considerable fraction of the whole height of the water-table. Over a long period or under normal conditions the GHYBEN-HERZBERG principle assumes that in a given place, for each foot of fresh water in porous rocks above sea-level, there is a depth of about 40 feet of fresh water below sea-level in the subjacent rocks. It therefore follows that if the head of the basal water-table above sea-level be changed by one foot, resumption of equilibrium requires that a corresponding change of 40 feet be made in the sub-sea-level portion of the lens.

The ground-water body above and below sea-level represents storage; for convenience, therefore, the two parts, respectively, above and below the sea-level plane will here be referred to as top storage and bottom storage. These terms will be applied both to the water itself, and to the geometric figure in the rock occupied by the water. The most important concept to be presented in this paper is that while there is an immediate response tending toward the establishment of equilibrium, following any change in the height of the water-table, the ratio of 40 to 1, in the amounts of water to be moved, precludes the possibility of instantaneous or even prompt accomplishment of the change required in bottom storage by the amounts and rates of change which in fact do occur in top storage in actual systems. It is easy to see that owing to the configuration of the caprock, which sets a limit to the area of free water-table as well as of free diffusion-zone, the numerical areas of these may be quite different and hence the volumes in a ratio different from 40 to 1. At Honolulu, assuming no material difference in porosity, top and bottom, it is most plausible to suppose that because of probable greater bottom areas, the ratio of volumes may be much larger than 40 to 1. However, even fairly wide fluctuations in the unknown volume-ratio do not materially affect the argument or conclusion of this paper. For example, at Honolulu for occasional short periods the water-table does rise at a daily rate corresponding to about five times the normal daily increment of water to the system, expressed in head-increases, the latter being mostly continuously dissipated so as not to result in rise of water-table. Or, in a year, a net increase of height of water-table equal to more than half the annual increment can be accomplished. The water necessary to provide this increase of top storage in these periods can be found in increased rainfall, or decreased draft, but it is quite impossible, short of very much longer periods, to find quantities of water 40 times greater to accomplish a complete corresponding expansion of bottom storage.

This condition is quite analogous to the problem of long-term effects and the factor of time emphasized by C. V. THEIS in a number of papers since 1935 [5]. It differs however in the discrete separation, rather than transitional connection, between the fast-responding, top or nearby part of the system, and the slow-responding, bottom or more remote part of the system. It is more closely parallel to the behavior of two reservoirs, one of 40 times the surface-area of the other and connected by a pipe long enough or small enough so that fluctuations in the larger, dependent reservoir are retarded markedly in relation to those in the smaller independent reservoir.

The dependence of bottom storage--It is important to recognize that with a fixed position of sea-level, the magnitude of bottom storage and the position of the surface of balance are dependent variables, necessarily following, even though lagging behind, the independent movements of the water-table, which is the free, upper surface of the top storage. Except change of sea-level, already excluded, no independent forces or changes can be applied directly to the bottom storage, even draft of water from the very bottom of a well which reaches to the bottom of bottom storage, is based on drawdown at the top of the well which is an artificial part of the free, independent water-table.

This does not deny that movement of water across the boundary between salt water and fresh water takes place, but simply asserts that these continuing processes are secondary to and integrated from the current and past primary, independent constant conditions or fluctuations of the water-table. Each new factor or pulsation is first applied by change in the water-table, general or local, and is then followed by the corresponding change in the bottom storage at a declining rate set by total permeability and water-quantities.

It is the chief point of this paper to discuss the causes, rates, and magnitudes of changes in the position of the diffusion-zone, or line of balance between fresh water and salt water. Figure 3 shows the elements of this hydraulic problem in an artesian system. In it there are two free surfaces, or air-water boundaries. One is the water-table AB and the other is the free surface of the ocean FG. Because of the relative freedom of movement of water of the ocean, as compared to water in permeable rocks, the latter free surface is practically at the position of the volcanic slope of the island or DE. Since water is practically incompressible any movement of the diffusion-zone can only be accomplished by a corresponding volumetric change at one or the other of the free surfaces. It should be recognized that whereas the Honolulu System is artesian in its present chief form of production, there is everywhere a free water-table within a few thousand feet of any point of draft. Change in this nearby water-table is the preponderant effect of draft; there does not appear to be reason to suppose that volume-change in the water or in the aquifer-structure can be a significant factor in the yield of this type of system. Actually a volume-change at any point in the interior of the saturated part of the permeable rock, and the inducing pressure-changes, will be felt at both free surfaces, in amounts and at rates which are proportional to the respective total permeabilities of avenues leading to these two free surfaces.

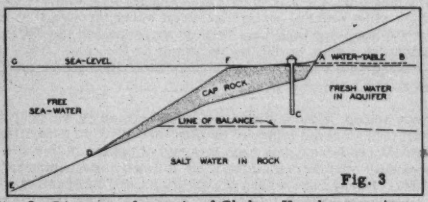


Fig. 3

Fig. 3--Diagram of margin of Ghyben-Herzberg system where artesian conditions obtain [For purpose of transfer of water between top and bottom storage due to head-lag, total stream-tube extends from free water-table surface AB, to free surface of the ocean FG, and stream-tube in more or less permeable rock, partly through and partly under cap-rock, extends from AB to DE, limits B, E, and G being not accurately known; any changes in volume of either top or bottom storage must of necessity be expressed in substantially same change at free surface AB, assuming fixed sea-level, and any change of line of balance requires a corresponding movement of entire content of stream-tube from AB to DE (see further discussion in the text)]

If, for example, there be continuous draft of water by pumping or otherwise from a well situated at C in Figure 3, there must be shrinkage of the total water-system by an equal amount. Because the water-table AB is very much nearer than the ocean surface FG hydraulically, the preponderant response will be at the water-table and will be deductible from the top storage, despite the fact that the actual water taken will have come from bottom storage. The effect on the free ocean-surface will be much smaller in actual volume and vanishingly small in change of level. This fact that the free surface responses are preponderantly felt at the water-table and that all changes in position of the diffusion-zone are induced by changes first indicated in the free surfaces, such as the water-table or in a well whose drawdown-surface is an artificial free water-table, clearly demonstrates the dependent character of the bottom storage and the diffusion-zone which defines its total volume. The ocean is so large in area, and the fluctuations in this free surface are so negligible, that sea-level is in this connection a fixed datum. Hence it appears that the earlier analogy of two reservoirs, connected by a small pipe, with the larger one 40 or more times the smaller in area, and only the smaller one accessible to changing additions and subtractions of water is sustained. The only access to the larger reservoir, plus or minus, is through the changing heads of the smaller. Continuous, nearly constant losses of fresh water across the diffusion-zone do not in any practical sense invalidate this picture, any more than small nearly steady leaks would do so in the reservoir.

Behavior of interconnected reservoirs--In order to discuss the elementary behavior of two reservoirs as a hydraulic analogue of the GHYBEN-HERZBERG system, certain assumptions are made (Fig. 4). Two reservoirs T and B are interconnected by a small pipe P. Reservoir B has a free surface-area 40 times that of Reservoir T. Both reservoirs T and B suffer slow leaks to a very large

Fig. 4

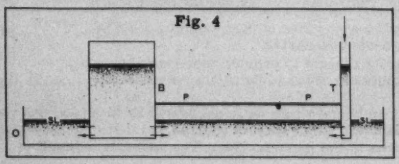


Fig. 4--Diagram showing small and large reservoirs, connected by small pipe as described in text as analogue to Ghyben-Herzberg system

reservoir O at head SL, and without additions these would eventually all fall to the level SL. We assume continuous additions to T at an average rate which has fixed an equilibrium head in T, and in B by transfer through P, such that this average amount of water is discharged by leakage continuously into the very large reservoir O. This is the historical condition in which we find the system. Let us assume that over a period of somewhat extended observation the mean level of T and B are substantially the same, but that frequently for very short or moderately long periods the rate of addition is above or below its normal value, or the rate of certain leakages from T are below or above their usual rate. In this case it is found that the water-level in T rises or falls at a rate which is not immediately reflected in B. A further assumption is that water moves through the pipe P at a rate which is directly proportional to the difference in water-level in T and B. Therefore at any time when by abnormal rates of addition or subtraction the level of water in T differs from that in B, the difference in head determines the rate of rise or fall of the dependent level B in its approach to the position of the independent level T. The departure in level of B from that in T may be called lag; if measured in feet of difference at a given time it will be head-lag, if measured in time required to reach a comparable head it will be time-lag.

It is evident that given a certain hydraulic capacity of P and proportionality of its discharge to the head-difference or head-lag, there would be, for any given rate of excessive addition to or loss from T, an amount of head-lag, which when reached would discharge water through P at a rate equal to 40/41 of the excess so that the head-lag would not further increase and the difference in head would remain the same, though both be rising, or falling, as might be the case. This limiting difference, fixed by a given rate of change in the head of the independent reservoir T and by the existing capacity of P, is designated as the limit of lag.

At any time after a given lag has been set up, if the additions or subtractions by which it was produced are to cease, the two levels will tend to come together by flow through P at a declining rate continuously determined by the residual head-lag. Any such process of approach to a limiting value at a rate proportional to the residual amount remaining to go follows a mathematical function known as a logarithmic decrement. In any case where the additions and subtraction to and from the top storage T come to close balance so that T is in a somewhat passive condition and there still remains a head-difference or lag between T and B, the balancing of T and B will take place by a change of T by 40 head- and storage-units and of B by one unit of the same kind, so that final balance would be reached at a level very close to the former position of B. This shows that in a static or inertia sense B might be regarded as the controlling element. However in an actual system any large change of T to approach B would in turn probably establish new relationships between its own gains and losses, and the level set by these would, as maintained, be the independent factor tending to pull the level of B toward it.

Diagrammatical illustration of GHYBEN-HERZBERG system--In order to set forth the behavior of such systems, there are presented below four cases of assumed behavior in a system having dimensions of similar order of magnitude to the Honolulu System. The assumed or derived data are not intended as valid or specific quantities for the Honolulu System and it is obvious that in this attempt to sketch the fundamental principle in a full-scale model, many details and complications of any natural system, recognized in general but unknown in detail, must be neglected. In the following tables are summarized the postulated and derived data for the four cases at critical stages. Table A gives general dimensions.

Table A--Data common to all cases

Area of infiltration	25 square miles[a]
Area of free fluctuating water-table	25 square miles[a]
Area of fluctuating diffusion-zone (lower boundary of fresh water)	25 square miles[a]
Porosity of aquifer	19.2 per cent[b]
Top storage per foot of head	1,000 million gallons
Bottom storage per foot of bottom equivalent	40,000 million gallons

[a]These three areas may overlap each other in part, but would not in most natural systems having identical boundaries.

[b]This value has been arbitrarily adopted to provide round-number values for areas and storage amounts in order to facilitate computation.

In Case I is postulated a system initially in balance both as to heads and as to intake and discharge. At the commencement of the first year the infiltration is doubled and that rate is assumed to obtain for one year, when infiltration returns to the former value. The immediate result is

heavy addition to top storage, followed by increasing addition to bottom storage as the rising head produces a negative head-lag (Fig. 5). There is evidently room for confusion between an algebraic and a geometrical point of view in determining what are to be called positive and negative head-lags. It is believed preferable to follow the latter and to designate as negative head-lag the condition when the bottom equivalent is less than the top head. Thus, a negative head-lag results in loss of water downward from top storage to bottom storage; a positive head-lag results in yield

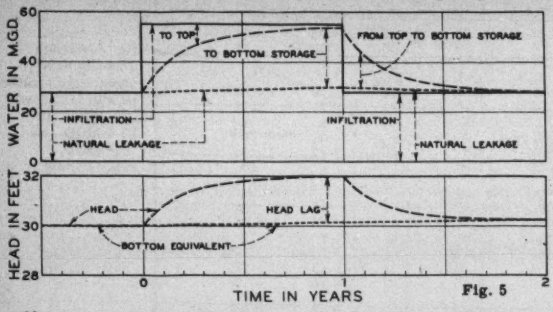
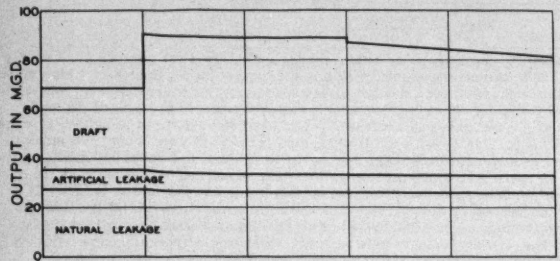


Fig. 5

Fig. 5--Graph showing head-changes and water-movement in Case I as described in text and tables; transfer-rate = 13.7 MGD



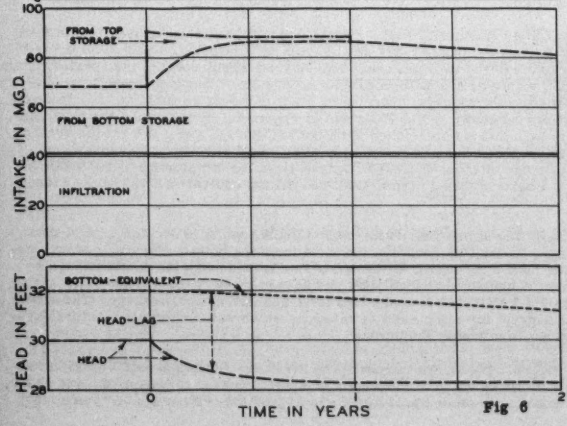


Fig 6

Fig. 6--Graph showing head-changes and water-movement in Case II as described in text and tables; transfer-rate = 13.7 MGD

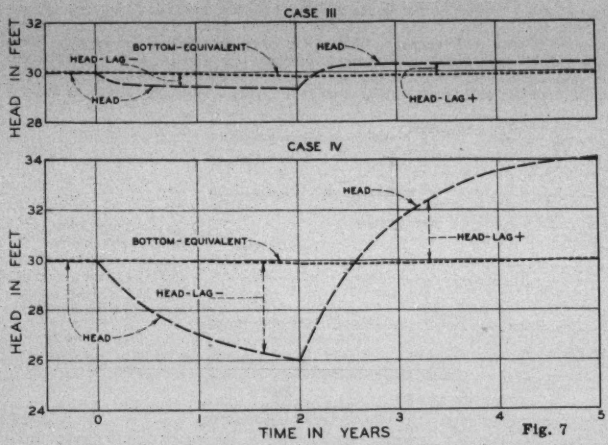


Fig. 7

Fig. 7--Graph showing head-changes in Cases III and IV; transfer-rates are 27.4 MGD and 2.74 MGD, respectively

of water from bottom storage to top storage or draft. By the end of the first year this has nearly reached the limit of lag. With the return of infiltration to the former value, the water which must be added to bottom storage because of the established head-lag has to be borrowed from top storage, and by the end of two years this head-lag has nearly disappeared, and the bulk of the additional infiltration, minus slight increases in natural leakage, has been delivered to bottom storage. Of the total of 10,000 million gallons of extra infiltration during the first year, about 700 million gallons was discharged as excess natural leakage during the two years, and about 240 million gallons and the remainder, or more than 9,000 million gallons, are in top and bottom storage, respectively. Hence, though the balance between top and bottom heads and storage is practically achieved, final return of the system to the postulated initial equilibrium between infiltration and natural leakage would require the eventual discharge of all the added storage through the declining excess of natural leakage--an exceedingly slow process which would approach completion by a logarithmic decrement of approximately 0.8 per cent per annum.

Case II differs from Case I in starting with a residual positive head-lag of two feet, and an intake consisting of 41.1 million gallons per day (MGD) from infiltration, and 27.4 MGD derived from bottom storage by virtue of the two-foot head-lag. At the beginning of the test-period, draft is increased by 21.9 MGD, a rate of 800 million gallons per annum. This increased demand is immediately met by draft from top storage, lowering of head, increase of head-lag, and increase of yield from bottom storage as shown in the Table and in Figure 6. By the end of the first year, the extra water needed is being largely furnished from bottom storage and if the excess draft is to be maintained it is evident that a temporarily steady state would shortly be reached with a total draft from bottom storage of about 47.6 MGD, a draft from the top storage of 1.2 MGD, a head lag of 3.48 feet, and a slow lowering of both head and bottom equivalent at about 0.43 feet per year.

However, it is assumed that at one year, with head at 28.28 feet, it is decided to hold the head constant at 28.28 feet. Under this decision, the yield from the bottom storage is slowly reduced with lowering of the head-lag, so that at the end of the second year, the additional yield from bottom storage which commenced at 21.9 MGD has been reduced to 14.9 MGD, while at the same time a saving of only 2.1 MGD has been derived from reduced natural leakage. These two examples may suffice to suggest the complexity of relations which would obtain in a natural system where all the values are continually fluctuating.

In the two parts of Figure 7 are shown the effects of the same changes in infiltration in two systems having markedly different rates of movement of water from top to bottom storage under the same head-lag, but identical in other respects. Case III postulates a permeability such that

Table 1--Area and storage-data, Cases I and II[a]

Item	Previous	Initial	0.50 year	End first year	Begin second year	1.5 year	End second year
Case I, rate of transfer 13.7 million gallons per day per foot of head lag							
Head	30	30	31.80	32.00	31.80	30.33	30.24
Bottom equivalent	30	30	30.07	30.19	30.23	30.23	30.23
Head lag	0	0	- 1.73	- 1.81	- 1.81	- 0.10	- 0.01
Rate of transfer	0	0	-23.7	-24.8	-24.8	- 1.37	- 0.14
Infiltration	27.4(1)	54.8	54.8	27.4	27.4	27.4	27.4
Natural leakage	27.4	27.4	29.0	29.2	29.2	27.7	27.59
Artificial leakage	0	0	0	0	0	0	0
Draft	0	0	0	0	0	0	0
Net change, top st.	0	+27.4	+ 2.1	+ 0.8	-26.6	- 1.67	- 0.33
Net change, bottom st.	0	0	+23.7	+24.8	+24.8	+ 1.37	+ 0.14
Case II, rate of transfer 13.7 million gallons per day per foot of head lag							
Head	30	30	28.52	28.28	28.28	28.28	28.28
Bottom equivalent	32	32	31.84	31.61	31.61	31.41	31.21
Head lag	+ 2	+ 2	+ 3.32	+ 3.33	+ 3.33	+ 3.13	+ 2.93
Rate of transfer	+27.4	+27.4	+45.5	+45.6	+45.6	+42.8	+40.2
Infiltration	41.1	41.1	41.1	41.1	41.1	41.1	41.1
Natural leakage	27.4	27.4	26.0	25.8	25.8	25.8	25.8
Artificial leakage	8.2	8.2	7.8	7.7	7.7	7.7	7.7
Draft	32.9	54.8	54.8	54.8	53.2	50.4	47.8
Net change, top st.	0	-21.9	- 2.0	- 1.6	0	0	0
Net change, bottom st.	-27.4	-27.4	-45.5	-45.6	-45.6	-42.8	-40.2

[a]Tables 1 and 2 have been calculated by successive approximation carried far enough to give a substantially correct picture, but for the present purpose rigorous computation to three or more significant figures was not deemed worth the effort. Rates of transfer and of natural and artificial leakage have been assumed proportional to head, assuming that the greater part of the movement follows Darcy's law. However, a considerable deviation from this law would not materially modify the conclusions.

27.4 MGD of water is transferred per foot of head lag. As will be pointed out later, there is reason to believe that this is a higher rate than the real one in the Honolulu Area. Case IV postulates a rate of 2.74 MGD, or one tenth that of Case III.

Both systems are assumed to start in equilibrium at 30 feet with infiltration equal to combined draft plus leakage at 41.1 MGD. Each is subjected to two years of infiltration at only two-thirds that of the previous equilibrium-period. At the end of two years, there follow three years of infiltration at four-thirds the first rate. These extremes are approximately similar in range to those known for rainfall in the Honolulu Area; they are probably greater than any possible range in infiltration and at least equal in range to any possible combinations of extremes of infiltration, draft, leakage, and the like, for periods of so much as two years. Under such extreme deceleration and acceleration in Case III, there is a total head variation of only 1.02 feet, whereas in Case IV, the variation is more than eight feet. Obviously, with a transfer rate of 27.4 MGD, the bottom storage operates as a hydraulic damping or regulating agent to a far greater extent than in Case IV with a rate of 2.74 MGD. This example, set up with magnitudes comparable to those of the Honolulu System, enables one to hazard the guess that the transfer-rate in the Honolulu System cannot be so great as 27.4 MGD, because the head of the Honolulu System does actually fluctuate through a range of five or six feet commonly in two- to five-year periods and under hydraulic accelerations and decelerations believed rarely to be so great as those postulated.

Unfortunately, estimation of the lower possible limit of the transfer-rate, even roughly, is more difficult, since the net value of accelerations and decelerations is probably much less than the values used, but is not accurately known.

Summary--The GHYBEN-HERZBERG principle implies not only a ratio of approximately 40 to 1 between the thicknesses of the portions of fresh ground-water below and above sea-level, respectively, but also implies a similar ratio between the amounts of water stored in these two portions, wherever the porosity of the aquifer and its area is the same in the two portions. Even where these change somewhat from top to bottom it appears that in most systems the ratio of

Table 2--Area and storage data, Cases III and IV

Item	Previous	Initial	One year	End second year	Begin third year	Three years	Four years	Five years
Case III, rate of transfer, 27.4 million gallons per day per foot of head lag (twice that for Cases I and II)								
Head	30	30	29.42	29.37	29.37	30.30	30.36	30.39
Bottom equivalent	30	30	29.89	29.85	29.85	29.84	29.88	29.91
Head lag	0	0	+ 0.47	+ 0.48	+ 0.48	- 0.46	- 0.48	- 0.48
Rate of transfer	0	0	+12.9	+13.2	+13.2	-12.6	-13.2	-13.2
Infiltration	41.1	27.4	27.4	27.4	54.8	54.8	54.8	54.8
Natural and artificial leakage	13.7	13.7	13.4	13.4	13.4	13.8	13.9	13.9
Draft	27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.4
Net change, top st.	0	-13.7	- 0.5	- 0.2	+27.2	+ 1.0	+ 0.3	+ 0.3
Net change, bottom st.	0	0	-12.9	-13.2	-13.2	+12.6	+13.2	+13.2
Case IV, all conditions same as Case III except rate of transfer is 2.74 million gallons per day per foot of head lag (one-tenth that for Case III)								
Head	30	30	27.02	26.02	26.02	31.50	33.58	34.10
Bottom equivalent	30	30	29.96	29.87	29.87	29.86	29.92	30.02
Head lag	0	0	+ 2.94	+ 3.85	+ 3.85	- 1.64	- 3.66	- 4.08
Rate of transfer	0	0	+ 8.05	+10.55	+10.55	- 4.5	-10.0	-11.2
Infiltration	41.1	27.4	27.4	27.4	54.8	54.8	54.8	54.8
Natural and artificial leakage	13.7	13.7	12.4	11.9	11.9	14.4	15.3	15.6
Draft	27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.4
Net change, top st.	0	-13.7	- 4.35	- 1.35	+26.05	+ 8.5	+ 2.1	+ 0.6
Net change, bottom st.	0	0	- 8.05	-10.55	-10.55	+ 4.5	+10.0	+11.2

bottom to top storage, as a whole, or per foot of equivalent head, will be a large number, greatly in excess of 1:1.

Owing to variable infiltration, leakage, and draft, and to the fact that these first directly affect the free water-table, the top storage is the independent or leading element of the pair and bottom storage is the dependent or following element.

Expansion or contraction of top storage by rise or fall of the water-table is followed by changes in the bottom storage of similar sign which take place at a rate determined by (1) the amount of head-lag and (2) the specific total permeability of the avenues connecting top and bottom storage.

Because of the large ratio between the two portions of the storage and the large amounts of water in bottom storage corresponding to actual rates and amounts of fluctuation in the top storage, in comparison to available excesses or deficiencies of water passing through the independent top storage, it is an inescapable conclusion that all changes induced in the bottom storage must lag considerably behind the changes in top storage and for the greater changes this lag must at least amount to some months and probably many years.

In a system which continues to fluctuate around a mean position of the water-table, the chief effect of such hydraulic inertia and lag of the changes in bottom storage would be to serve as a stabilizing agency, damping out the larger oscillations of the top storage by transfer to or from the bottom storage.

Unfortunately, most systems in which man has an interest have suffered progressive lowering of the water-table, which cannot be permanently restored to its former, natural position. Systems which have thus suffered a large net lowering of water-table have temporarily benefited not only by draft from the top storage, but by a much larger, longer-continued, perhaps still-continuing, and often unsuspected yield from bottom storage.

Chief unknown factor in the process is the specific total permeability or rate of yield from bottom storage per foot of unbalance. If this be assumed to be too large the duration of lag and of continuing yield is reduced, but the large amounts of water yielded tend to drown out the fluctuations in the water-table to an extent that is inconsistent with the known facts; in this case the benefit from this storage is initially great but declines rapidly. If the rate be assumed too small, the initial amount of benefit is reduced but it declines in amount much more slowly and endures much longer. Extremes in assumed rates in either direction lead to consequences that appear inconsistent with the facts, but in a large and complicated system making an inventory of gains

and losses sufficiently precise to fix closely the constant of hydraulic inertia between the top and bottom storage is a very complex problem.

Nevertheless, it is believed that this factor is the controlling one in any functional GHYBEN-HERZBERG system and that without an approximate determination of its magnitude, any other inventories of gain and loss in such a system will certainly be subject to large errors and will be of slight value in a long-term sense.

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AMERICAN GEOPHYSICAL UNION

TWENTY-THIRD ANNUAL MEETING

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THE IMPORTANCE OF THE ROSS SHELF-ICE TO STRUCTURAL GEOLOGY

Walter H. Bucher

Displacement over long distances of sheets of rock that are thin in comparison to their lateral extent plays a larger role in orogenic deformation than is generally recognized. The shape of "thrust-sheets" is, of course, well enough understood, as the word itself shows. But we find it still difficult to think concretely of the processes involved in their movement when we are confronted with specific cases. In the so-called "Cumberland thrust-block", which lies athwart the tristate corner of Kentucky, Virginia, and Tennessee, a slice of rock about 18 miles wide, 127 miles long, and little over one mile thick was sheared off nearly parallel with the bedding and shoved a distance of at least seven miles [see 1 of "References" at end of paper]. The slice was torn from its flat-lying environment along tear faults that bound it at either end, the Jacksboro [2] and Russell Fork [3] faults. They dip more or less steeply toward the thrust-slice. As the latter moved forward on a slightly inclined plane, older rocks came to lie on younger ones along the tear-faults giving them the false appearance of high-angle thrust-faults. In addition, however, the whole slice was rotated which introduced an actual thrust-component across the southwestern tear-fault and produced cross-wrinkles, features which have been analyzed by WENTWORTH and RICH [1, 3].

This rather small but almost perfectly preserved thrust-mass is the only one known to the writer in which all significant details of structure have been successfully explained in terms of the movement of a thin sheet torn from its environment by orogenic shoving [1, 3, 4]. As far as the writer can tell, its significance is not generally appreciated. It offers the simplest example of folds that exist in a thin, sheared-off skin; wrinkles in what remained essentially a flat plate as it moved, in contrast to the close wrinkling of the thin layer that was thrown into folds in the Jura Mountains.

Parenthetically we may note that this distinction of folds that are limited to a thin thrust-slide and others which extend to greater depth is fundamental in the interpretation of complex structures such as those of the folded Appalachians. The structural behavior of the Cumberland thrust-slice is typical rather than exceptional of the thrusting in the Appalachians. Witness, for instance, the parallelism that exists between the beds above the thrust-plane in such conspicuous thrust-slices as that which is bounded below by the Pulasky Fault in the Roanoke Region [5].

Even the largest thrust-sheets are but details in the movements that produce the structure of the Earth's great orogenic belts. It is becoming increasingly probable that these major movements as a whole are executed by only an outer fraction of the Earth's crust. This line of thought follows rather inevitably from the epochal discovery of belts of strong negative gravity-anomalies which coincide with belts of active orogeny. VENING MEINESZ, their discoverer, has discussed their structural implications in the second volume of his treatise on "Gravity expeditions at sea" [6].

The magnitude of the gravity-anomalies demands a great downward thickening of the acid, lighter outer part of the crust. As the present writer has shown, in view of the nature of the physical behavior of the two parts of the crust, this must be accomplished by a downward thickening of the whole crust through which the acid part is drawn downward into a light "root". Speaking of this outer, acid, downward-buckling zone, VENING MEINESZ says "... at a certain stage of the phenomenon, it will begin to bulge outwards in irregular folds, which will cover the downward buckling of the main crust-layer". The word "cover" is a neutral expression for the differential movement of this outer "skin" with reference to the divergent displacement of the deeper parts of the crust. In a diagram VENING MEINESZ draws the line that separates the outer upward-wrinkling skin from the rest of the crust extending horizontally for a distance of over 500 miles from the axis of downward buckling [7].

This train of thought leads us to visualize the development of such remarkable belts of folding as that of Iran, Afghanistan, and Balutchistan as the wrinkling of a mere skin, say something like ten miles thick, but up to 750 miles wide and several times as long, which forms a constantly narrowing belt that is weak because it lies over an active zone along which the crust adjusts itself to shrinking Earth chiefly by downward buckling.

But the crust itself must, in the course of this adjustment by local yielding, move differentially over the asthenosphere. Once again the scale of the picture enlarges and we see areas measuring thousands of miles across and tens of miles in thickness being displaced not only with

reference to what lies below them, but also with reference to each other. On this scale, what are mere tear-faults in thrust-sheets appear now as major rift-zones, such as the San Andreas Rift, the Garlock Fault, or some of the remarkable faults which A. W. JOLLIFFE is exhibiting at this meeting on air-pictures from the Northwest Territories of Canada. They are visible expressions of the struggle for space that is going on among parts of the crust as yielding takes place now here, now there by buckling downwards and shearing off outwards as the Earth's body shrinks.

If this picture is correct, it must become a major aim of the structural geologist to use every opportunity that offers itself of studying the behavior of relatively thin plates of crystalline materials subject to stress under conditions that permit at least a certain amount of plastic yielding. The Ross Shelf-Ice offers a unique opportunity for such a study. It covers the southern half of the Ross Sea, the embayment that cuts deeply into the Pacific quadrant of Antarctica. It breaks off at its northern front in a cliff that varies in height from 5 to 200 feet--the "Ross Barrier" of the earlier literature. This front is around 600 miles long and the distance from it to the head of the Ross Sea measures around 500 miles. An unknown inner part of this vast ice-sheet must be resting on the shallowing sea-floor. A large outer part, on the other hand, must be afloat. Throughout most of its large area, this sheet of ice is in motion due, at least in part, to the crowding into it of large glaciers [8]. Beyond the point where a large glacier from the bordering mountains joins the shelf-ice, the latter is thrown into anticlines and synclines which decrease in height and increase in wave-length much like the Appalachian folds to the West of the Blue Ridge axis. These and the other features yet to be mentioned have been described and well illustrated especially by GOULD [9].

High welts of ice with characteristic diagonal en echelon wrinkles occur along the contact of land ice and moving shelf-ice. They bring to mind the oblique cross-structures of the Colorado Front Range. Farther out, as for instance near the center of the Ross Shelf-Ice between latitudes 81° and 82°, huge crevassed areas seem to indicate local retardation, as by contact with shallow sea-bottom. Large shear-zones which mark zones of differential movement between adjacent expanses of shelf-ice, show structures which deserve close study. These include tilted and diagonally fractured blocks that recall the remarkable structure of the Pryor Mountains which has been so ably described by BLACKSTONE [10].

The most instructive combination of structural features is exhibited by the relatively thin sea-ice of the Bay of Whales on the side of which Little America is located. This Bay, which extends about 15 miles back of the ice-front, was wide open when first seen. It lies in the lee of an ice-covered island around which the shelf-ice streams. Since first observed, the sides of this Bay have been steadily closing in, throwing the sea-ice into systems of folds traversed by oblique shear-zones. A comparison [11] of AMUNDSEN'S map, made in 1912, of this model area of ice-tectonics with those brought back by BYRD'S three expeditions (1928-30, 1933-35, and 1939-41) makes it possible to trace the changes in outline and connect them with the changes in the fold-pattern which have been recorded on hundreds of aerial photographs [12]. Triangulation by ground-parties and other observations of quantitative nature as, for example, concerning the thickness of the ice, are available and permit a first approach to a quantitative study of the movements involved.

The importance of such studies for the understanding of the features produced by the movements of the Earth's crust and thinner sheets within the orogenic zones must have been evident to anyone who read GOULD'S paper of 1935. So much material has now been accumulated that a special effort is in place to record in terms of rock-tectonics the details of structure of a few carefully chosen regions, above all, of course, the vicinity of the Bay of Whales. For that purpose a "Committee on the Structure of the Ross Shelf-Ice" was organized by the Division of Geology and Geography of the National Research Council with the writer as general chairman [13]. The first task which this Committee set itself is the construction of tectonic maps of the chosen areas. The direction of this work was placed into the hands of P. A. SIPLE who has been in charge of the map-work at the office of the United States Antarctic Service where he is working in close cooperation with F. A. WADE, the Senior Scientist of the Expedition. Through a liberal grant, the Geological Society of America has made possible the employment for one year of a technician trained in the mapping from oblique photographs. This work is to begin on July 1, 1942. Its outcome holds much of promise for the understanding of orogenic deformation.

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[7] Loc. cit., Fig. 19, p. 119. Attention must be called to the essential difference that exists between this concept and the diagrammatic picture of the downward buckling which was developed by KUENEN from experiments and accepted by H. H. HESS. According to these authors the crust as a whole buckles down like a piece of paper held between approaching hands, wrinkling and scuffing only the young sediments that have accumulated in the deepening depression. Unfortunately the behavior of the films of paraffin or of mixtures of paraffin and liquid hydrocarbons that were used in the experiments was due primarily to their surface-tension with reference to the water on which they floated. There is no counterpart to this condition in the Earth's crust. There remains only one alternative, a general thickening of the crust followed by a progressive shearing off of an outermost "skin" as outlined above. See PH. H. KUENEN, The negative isostatic anomalies in the East Indies (with experiments), Leidsche Geol. Mededeel., v. 8, pp. 169-214, 1936; H. H. HESS, Gravity anomalies and island arc structure with particular reference to the West Indies, Amer. Phil. Soc., Proc., v. 79, pp. 71-96, 1938.

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[11] A very instructive map has been drawn by PAUL A. SIPLE and was exhibited at the annual meeting of the Division of Geology and Geography of the National Research Council on May 2, 1942.

[12] This address was illustrated with lantern slides made from air photographs supplied by Drs. GOULD, SIPLE, and WADE to whom the writer wishes to express his gratitude.

[13] Committee members: MAX DEMOREST, L. M. GOULD, F. E. MATTHES, P. A. SIPLE, F. A. Wade. Others may be added eventually in connection with the projected correlation with orogenic structures.

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STRUCTURES IN THE CANADIAN SHIELD

A. W. Jolliffe

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No balanced picture of structures in the Canadian Shield can be presented now nor for some years to come. Only a very small fraction of the 2,810,000 square miles comprising the Shield has been mapped or described in detail. However, sufficient has been done to establish that (1) certain types of structure are peculiar to the Shield, or at least are more common or better exposed there than in more recently deformed regions and (2) certain areas within the Shield by

Fig. 1--Looking northeast along fault near Hornby Bay, Great Bear Lake [Lineament which here marks the fault can be traced about 80 miles; rocks on left (late Pre-Cambrian sandstone and conglomerate) have been downthrown relative to those on right (early Pre-Cambrian intrusive and extrusive rocks); direction and amount of lateral displacement is unknown; movement and vein filling along fault have been recurrent (Royal Canadian Air Force photograph A3783-41)]

Fig. 2--Looking north towards fault at Cameron Bay, Great Bear Lake [Moderately-dipping conglomerate in center of photograph strikes into high hill of porphyry on left; quartz veins and stockworks mark fault which shows an apparent right-hand lateral displacement of about three miles (D. F. Kidd, Great Bear Lake area, Northwest Territories, Canada, Geol. Surv., Summary Rept. 1932, pt. C, p. 18, 1933]

Fig. 3--Looking northeast along fault marked by large quartz vein near Marian River, north of Great Slave Lake [Fault shows an apparent right-hand lateral displacement of between seven and eight miles (Royal Canadian Air Force photograph A4740-81 L)]

virtue of their almost continuous outcrop and excellent exposures are particularly suited to detailed structural mapping. A study of the structures within such areas may at least suggest promising fields of research. This paper deals with but two of the many structural types found within the Canadian Shield--strike-slip faults and steeply-plunging folds. Most of the illustrations are drawn from the northwestern part of the Shield where bed-rock structures are exposed in a fashion duplicated possibly nowhere else in the world.

Strike-slip faults --Throughout the northwestern part of the Shield rectilinear topographic features or lineaments are very apparent from the air [see 1 of "References" at end of paper]. The lineaments are formed by reasonably straight shore-lines, water-courses, scarps, valleys, or ridges, and some of them can be traced for distances of several hundred miles. Many of the lineaments are known to mark major faults all of which stand about vertical.

Within an area of about 15,000 square miles extending east and south-southeast from Great Bear Lake, the great majority of known faults trend about northeast. Of three faults where direction of vertical movement is known, the northwest block moved relatively downwards in two cases and upwards in one [2] (Figs. 1 and 2). The amount of vertical movement is probably of the order of a few hundreds or thousands of feet. The horizontal movements, where these can be measured, seem to be of much greater magnitude and in probably all cases the northwest side has moved relatively northeastwards, that is, the strike-slip movement is right-hand (Figs. 2 and 3). Many of the faults are marked by unusually large quartz-veins which, with bordering stockworks, attain widths of as much as 1,000 feet. Several afford evidence of recurrent movements at widely separated intervals. The latest vein-fillings along certain faults cut Late Pre-Cambrian diabase dykes [3].

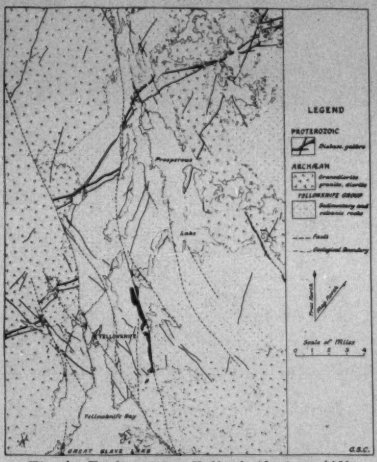

Fig. 4--Fault-pattern Yellowknife Area (All faults show left-hand strike-slips which together total about 11 miles)

Southeast of the aforesaid region is an area of about 30,000 square miles on either side of Yellowknife River that is characterized by north- to northwest-trending faults showing left-hand strike-slip movements. These have been studied in most detail in the vicinity of the town of Yellowknife on the east side of the north arm of Great Slave Lake. The Yellowknife Area lies at the intersection of two fault-systems (Fig. 4). One extends at least 50 miles north up Yellowknife River Valley. The other trends north-northwest for about 70 miles and probably continues twice this distance farther. The movements along the faults have been largely or wholly horizontal and in each case the east side has been shifted relatively northwards. Displacements on individual faults range up to five miles and, across a width of ten miles, the total horizontal offset produced by the faulting is about 11 miles. The faults branch and join as indicated on Figure 4. Where two or more faults join to form a single fault, the sum of the offsets on the branches is about equal to the offset on the main fault. The faults are marked by intensely sheared rock from an inch to more than 100 feet wide. The width bears little relation to the amount of displacement and may vary greatly along a single fault. It is greatest where a fault changes strike (Fig. 6).

Fig. 5--Looking south along West Bay Fault, Yellowknife Area [Fault shows a left-hand lateral displacement of 3-1/2 miles (Royal Canadian Air Force photograph A5032-53 L)]

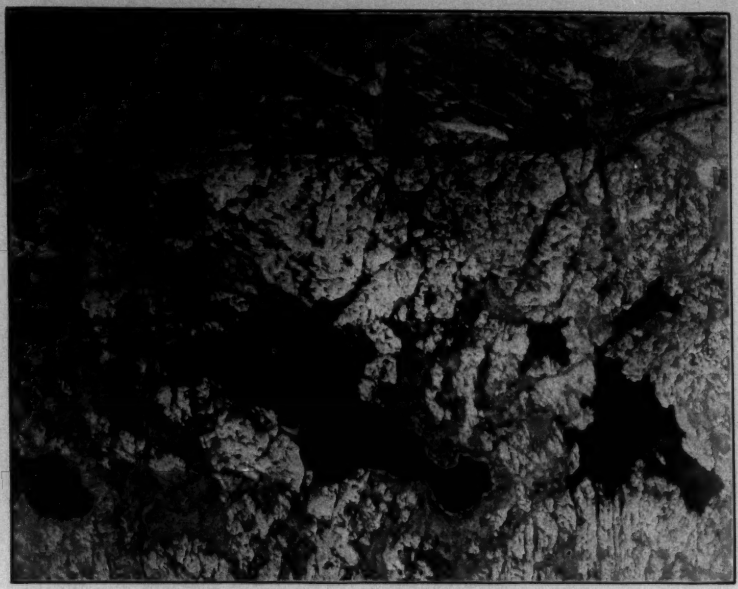

Fig. 6--Vertical view of West Bay Fault showing zones of parallel shearing [Near point of change of strike the fault is marked by more than 100 feet of sheared rock; a mile north, near small lake in photograph, 3-1/2 miles of differential lateral movement has taken place within a drift-filled trench about a foot wide bounded on either side by relatively unsheared rocks (see Fig. 7); area covered by photograph is about 10 square miles (Royal Canadian Air Force photograph A5612-27)]

Fig. 7--Shear-zone a foot wide marking fault along which 3-1/2 miles of lateral displacement has occurred (Granodiorite to left and lavas to right are relatively unsheared)

Fig. 8--Looking southwest along fault at McDonald Lake, south of east arm of Great Slave Lake [Lineament marking this fault can be traced for more than 300 miles; direction and amount of lateral displacement is unknown; here downthrow side is on north, farther east the downthrow side may be on the south (Royal Canadian Air Force photograph A5120-105 R)]

Many of the major faults appear on certain outcrops as little more than cracks commonly bordered by an inch or two of cherty mylonite holding numerous tiny pyrite crystals. The fault along the west side of Yellowknife Bay at a point two miles north of the town is marked by strong shearing more than 100 feet wide. One and one-half miles farther north the same fault follows a drift-filled trench a foot wide that crosses relatively unsheared rocks (Fig. 7). Three miles beyond this point the fault holds a quartz-vein and stockwork up to 180 feet wide. Movements on the Yellowknife faults took place largely or wholly subsequent to the intrusion of Late Pre-Cambrian diabase.

Along and to the south of the east arm of Great Slave Lake are a number of faults striking northeast. The most prominent of these lies along the south side of McDonald Lake and can be traced with reasonable certainty for more than 300 miles (Fig. 8). Certain features suggest that the vertical movements have been in opposite directions at either end of this fault, and that along this as well as other faults in the vicinity right-hand strike-slip displacements amounting to several miles have occurred [1, p. 498]. Diabase dykes, presumably of late Pre-Cambrian age, cross some of the faults without offset.

Vertical or steeply-dipping faults showing relatively large strike-slip movements are found elsewhere in the Canadian Shield. One of the better known of these is the Horne Creek Fault at Noranda, Quebec [4]. This fault trends east-west and shows a right-hand strike-slip of at least two miles. Recurrent movements, perhaps not all in the same direction, have taken place along the fault, the latest of which cuts Late Pre-Cambrian diabase. The Horne Creek Fault is probably a branch of the still larger Cadillac-Malartic break.

Fig. 9--Steeply-plunging folds in early Pre-Cambrian sedimentary rocks three miles east of Yellowknife, Northwest Territories (Royal Canadian Air Force photographs A5612-4,33)

In summary, many faults in the Canadian Shield are known to follow essentially rectilinear vertical fractures that extend laterally for distances up to several hundreds of miles. None of them is known to mark major vertical displacements whereas a number show strike-slip movements amounting to several miles. From this it is inferred that the fault-movements were dominantly horizontal, of the same general nature as those along the San Andreas Rift. Movements along many of the Shield faults were recurrent, the most recent being Late Pre-Cambrian or even younger in age. Important ore-deposits (Noranda, Yellowknife) may be related to some of the faults.

Only recently have strike-slip faults been ranked with other major structural features of the Earth's crust [5]. At least certain features of such faults can be studied more profitably in the Canadian Shield than elsewhere. In the northwestern part of the Shield in particular the general fault-pattern is evident on aerial photographs. The direction and amount of lateral displacement can be determined with certainty as marker horizons, offset by the faults, commonly stand about vertical. Shearing and vein-filling along faults are exposed for study in many places.

Steeply-plunging folds--Folds with a nearly vertical or even an overturned plunge are relatively common in Early Pre-Cambrian rocks. They appear to be rare or absent in more recently deformed regions. An anticline with an overturned plunge has been described from the northern Adirondacks and has been called a "pseudo-syncline" [6]. A comparable structure occurs in the Opemiska Area, Quebec, where a fold with an amplitude of more than two miles has the form of a steeply-plunging anticline whereas it is actually an upside-down syncline. The strata involved in this fold are overturned both on the limbs and along the plunge [7]. Other steeply-plunging folds are described from the Malartic District in Quebec, and the Porcupine, Matachewan, and Larder

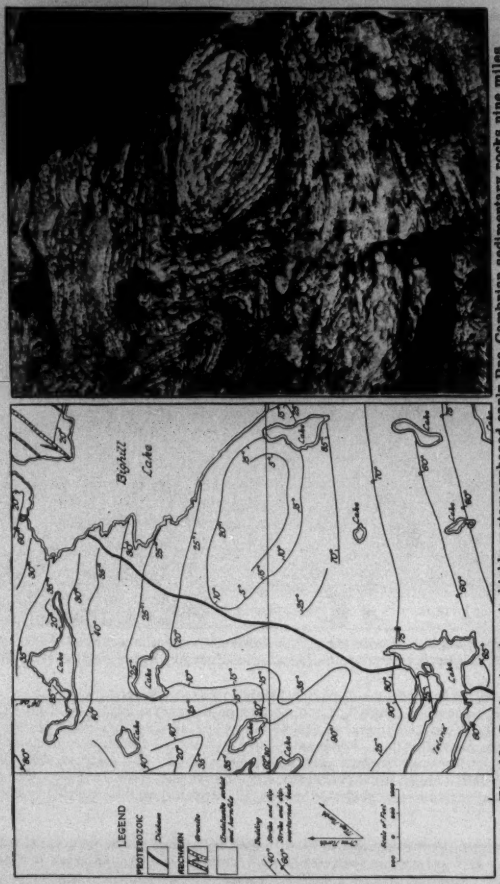

Fig. 10--Basin structure in highly metamorphosed early Pre-Cambrian sedimentary rocks nine miles east of Yellowknife, Northwest Territories (Royal Canadian Air Force photograph A5612-42)

Lake districts in Ontario, and have been termed "independent drag-folds".

> "These usually have a steep pitch and are especially typical of the deeply eroded stage of tectonic disturbance as seen in the older Pre-Cambrian. They appear to have been formed after the main folding by a predominantly lateral movement acting on already steeply dipping strata. Big thrust-faults, often having a horizontal displacement of several miles, are probably the result of the same stresses." [7, pp. 114-115]

Similar folds occur in the Lake Nipigon District of Ontario and have been called "secondary folds" produced "by indirect pressure resulting from the action of a shearing stress" [8].

The northwestern part of the Canadian Shield presents no exception to the above. Folds with

steep or overturned plunges occur as well as those of more normal attitude. Figure 9 shows a series of steeply-plunging folds in Early Pre-Cambrian sedimentary rocks east of Yellowknife. Six miles farther east more highly metamorphosed members of the same series lie in gentle basins and domes (Fig. 10). The large percentage of outcrop and a remarkable preservation of original structures (notably grain-gradation) in the beds aid in factual detailed structural mapping in this vicinity. Of four plunges measured within the area shown in Figure 9, three are vertical and one (near latitude 62° 30′, longitude 114° 15′) is overturned at 70°. Shattering along the axial lines prevents accurate measurement of plunge for the other folds but presumably they are similar. The axial planes of these steeply-plunging folds lie about at right-angles to the actual trend of the bedding across the area. That is, these folds, unlike some of the steeply-plunging folds in Ontario and Quebec, are not in the nature of drag-folds formed by rotational stress, but appear to have been formed by essentially simple compression acting end-on to a series of beds already tilted to a vertical or overturned attitude.

In passing, attention may be drawn to the relative reliability of various criteria for determining tops of beds in such highly deformed non-fossiliferous strata. The Yellowknife area has proven particularly enlightening in such a study [9]. Within an area of about 70 square miles more than 4,000 top determinations were made based on original structures and of this number perhaps ten were conflicting. By original structures are meant such features as grain-gradation, scour, and cross-bedding in sedimentary rocks, and pillow-shape and grain-changes in lava-flows. On the contrary, imposed structures such as cleavage and drag-folds, while commonly helpful in interpreting the form and position of folds, are in many instances misleading when used to establish stratigraphic succession in highly folded strata. The fold with an overturned plunge of 70° in Figure 9 supplies a case in point. Minor drags on the limbs of this fold have a similar plunge. The only apparent cleavage is a strong slaty cleavage in argillaceous beds which is about parallel to the axial plane of the fold, that is, it strikes northwest and dips about 50° to the southwest. The relations between these features and the bedding around this fold indicate that the latter is a syncline plunging steeply to the southeast and overturned towards the northeast, and that successively younger beds lie to the southeast. Obviously the fold has a synclinal form but regional considerations as well as numerous top determinations based on original structures within the beds demand that the younger strata lie to the northwest and prove that the fold is actually an upside-down anticline. That is, in highly deformed regions the relations between cleavage, drag-folds, or similar imposed structures and bedding may be helpful in indicating the outward forms and positions of folds, but they do not supply a completely reliable method for determining stratigraphic sequence.

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FABRIC ANALYSES OF ROCK-FLOWAGE

Ernst Cloos

(Abstract)

By far the major portion of crustal deformation takes place by flowage. Rock-flowage is meant here as representing plastic yielding and excludes ruptures of all kinds like joints, faults,

thrusts, fracture-cleavage, etc. It may include, however, fractured mineral grains or boudinage, and includes rotation and bending of grains, granulation, recrystallization, elongation of particles, bending of strata or foliation. In spite of its importance deformation by flowage is comparatively little known, very difficult to evaluate quantitatively, and at times very much neglected as a factor in folding. Flowage-phenomena in igneous rocks have been studied for many years but quantitative measurements are scarce. Determinations of flowage-directions in metamorphic rocks are easily possible by fabric analyses. Quantitative determinations are possible only where primary value or shapes of units may be known as for instance pebbles, amygdules, or oolites.

A systematic analysis of oolite deformation was begun by the writer in the Cambro-Ordivician limestones in Pennsylvania and Maryland. The results show very clearly that in several hundred localities there is a definite maximal direction of elongation dipping east within the cleavage-plane in the South Mountain uplift and the area adjacent to the west, a mean axis of deformation is parallel to the fold-axes, and the shortest deformational direction is perpendicular to the cleavage-plane. Flow-cleavage becomes more intense due to mineral alignment as the axial ratio increases from 1.2:1 to 7:1. Cleavage is everywhere a flowage-plane and due to mineral reorientation due to flowage.

In the Appalachian geosyncline folding has taken place to a large extent by flowage and by bending of strata. It has long been known that beds thicken in anticlines and synclines and are thinner along their limbs. Where flowage has taken place at large angles to the bedding planes the distance between beds has increased. If cleavage intersects bedding at large angles bedding has also increased in thickness.

A review of the literature and field-observations shows very definitely that many measured thicknesses are from anticlinal crests in large folds where cleavage transsects bedding at angles from 70° to 90°. Such type-sections are invariably thicker than others along limbs of folds and conclusions have been drawn that such variations of stratigraphic thicknesses represent variations of thicknesses of deposition, depths of troughs, etc. Maps showing sedimentary distribution, correlation-charts, and much other material is based on innumerable such type-section measurements without regard for possible distortion due to folding and rock-flowage.

The much-discussed concept of geosynclines is based largely on measurements of stratigraphic thicknesses but the question has hardly ever been discussed whether folding takes place where sediments are thick (in geosynclines) or sediments are thick due to folding.

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THE MAJOR DEFORMATIONAL PATTERNS CHARACTERISTIC OF THE EARTH'S CRUST AND THEIR MECHANICS-OF-ORIGIN

W. T. Thom, Jr.

The sum of available geophysical and geological information has at last advanced to a point where it is possible to state with confidence that certain major deformational patterns are characteristic of the Earth's crust, and that the mechanics-of-origin of these patterns can be confidently postulated on the basis of ordinary physical and engineering experience.

In the past incomplete (and partly incorrect) evidence regarding geotectonic problems has led to much uncertainty and disagreement--but with the accumulation of volcanological-seismological, geodetic-and-gravitational, and topographic-and-geologic evidence, the total evidence has fallen into focus and the general terms of the picture stand clearly revealed, showing that the Earth's crust can move (and is moving) laterally with respect to the centrosphere, that these movements are differential and in various directions, that surpluses of crustal area (as in an ice-floe or ice-pack) are recurrently eliminated by crumpling and overthrusting along interconnecting linear zones of weakness and fracture, and that the deformational patterns observed are primarily due to compression (with incidental tension and twisting). This compression operates in a relatively strong, brittle crust, underlain by a "zone of isostatic adjustment" characterized (either continuously or recurrently) by much greater mobility.

The pattern of the seismic-and-volcanic zones--The world's major seismic areas are essentially coincident with the world's great linear zones in which active mountain-making is now taking place, and these orogenic zones are in turn coincident with segments or arcs of certain great

circles, along which fracturing and buckling of the crust is being caused by the differential horizontal movements of the several main crustal segments outlined by these interconnecting fracture-systems.

Probably the best known of these seismic and tectonic belts is the one lying on the great-circle segment extending from Portugal, along the Alpine-Himalayan-East Indian zone, out to the Samoan-Tonga knot, or junction-point. A second (connecting) great-circle zone begins in the East Indies and extends through the Philippines, Japan, and the Aleutians to the Mt. McKinley junction-point, there in turn connecting with the western American seismic zone which extends from Alaska to Cape Horn, with an interconnected side branch extending through the West Indian arc. Another major seismic belt follows the Mid-Atlantic Ridge, crosses the Arctic Ocean, and extends southeastward across Siberia to join with the East Asian-Alaskan fracture-system. And a final zone extends southward from Tonga to the Kermadecs and New Zealand.

As is well known, the world's main volcanoes either are found within the seismic belts mentioned above, or are situated along linear zones where tensional fracturing of the crust has been produced by secondary torsional movement, or by differential crustal shifts along straight-line fractures.

The topographic-and-tectonic pattern--With the accumulation of sonic soundings it has become manifest that the Earth's seismic-and-volcanic belts (whether emergent, or submerged) are everywhere featured by great linear mountain-systems, which rise abruptly and continuously above both continental and suboceanic lowland platforms.

Moreover, as geologic study of mountain ranges has progressed it has also become clear that each fully developed mountain-system is featured by a major series of connecting fracture-planes, which extend obliquely downward through the Earth's crust. Along these oblique-fracture planes the elevated ranges have been thrust relatively forward and upward onto and partly across the contiguous geosynclines, which have marked the depressed edges of the adjacent "foreland" blocks.

In places the "linking" of a series of these oblique-thrust planes has produced a series of mountain arcs, as along the East Asian Coast. In other places, these dominant thrust-faults are offset laterally by great linear flaws or shift-zones (such as the San Andreas Rift), which separate the edges of two blocks that are either being shoved in opposite directionrs, or are being moved in the same direction, but at different rates of speed.

The geodetic-and-gravitational pattern--Though various tentative conclusions regarding the mechanics of crustal deformation have been developed during the past century on the basis of seismic, volcanologic, topographic, and tectonic evidence, it was not until recently that a definite confirmation of certain of these conclusions was made possible by evidence accumulated through geodetic and gravitational studies. These studies have proven (1) that a belt of subnormal gravitational attraction characterizes the foothills' zone of the Himalayas and that a similar condition also characterizes most (if not all) other great mountain ranges, (2) that the Earth's crust generally is in at least approximate isostatic equilibrium (and therefore must have undergone continuous, or recurrent, isostatic readjustment), and (3) that in regions of active mountain-building isostatic equilibrium is being locally and systematically disturbed by the mechanical downbuckling of strips of light crustal material, in belts subjacent to the slopes which lead downward from active island-arcs and mountain ranges into their parallel foredeeps.

The compilation and analysis of available gravitational data on a world-wide basis show that relict residuals of similar gradational "negative strips" are also preserved in association with mountain ranges belonging to previous generations, thus confirming the idea that crustal downbuckles and "negative gravity-strips" have been normal mechanical consequences of the operation of the mountain-building process throughout the Earth's history.

Summary and conclusion--(1) An analysis of the available geophysical, geodetic, and geological evidence regarding the world's seismic, volcanic, and orogenic zones indicates that the whole of the Earth's crust is undergoing a systematic deformation, under mechanical conditions roughly simulating those operative during the deformation of ice-floes and ice-packs--crustal rupture and deformational movement, both now and in the past being chiefly concentrated along the margins of crustal plates which have broken apart along lines approximating arcs of interconnecting great circles.

(2) The gravitational-plus-geologic data combine to show that an isostatic or flotational equilibrium is broadly characteristic of the main lowland segments of the Earth's crust, and also

that linear belts of negative anomalies (induced by mechanical crustal-downbuckling) habitually have characterized the active seismic-orogenic zones.

(3) The existence of essentially universal compressional stress within the crust is clearly indicated, as is also the capacity of segments of the Earth's crust to glide laterally over the sub-crust.

(4) Such differential horizontal glidings of crustal segments have recurred throughout geologic time, have been productive of great linear overthrusts in places, and elsewhere have produced great rifts of the San Andreas type--these rifts being vertical fractures or fracture-zones extending downward completely through the Earth's crust, and separating crustal plates moving at different rates, or in opposite directions.

(5) As would be expected, frictional resistances along such rifts have characteristically produced torsional shear and fold deformational patterns in the rift-border areas, and the renewal of movement along old rifts is also made manifest in places by en echelon fault-zone development, or "wall-paper-tear" patterns in strata deposited above the old rift-traces.

(6) Lateral crustal shiftings now taking place are definitely sufficiently rapid to induce zones of appreciable isostatic anomaly; they are almost certainly capable of accounting for the cutting (and drowning) of most, if not all, of the known submarine canyons; they are quite certainly sufficiently rapid in active regions to induce appreciable local distortion of established triangulation control-nets within a fairly brief period of years; they are taking place under dominant tangential compression, with movement facilitated by the mobility of the material in the zone of isostatic adjustment; and they are characterized by the movement of crustal plates or shields, bounded either by linear shears, or by belts of abnormally weak or thin crustal material.

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AMERICAN GEOPHYSICAL UNION

TWENTY-THIRD ANNUAL MEETING

MINUTES GENERAL ASSEMBLIES

AND SECTIONS

Washington, D. C.
April 3 and 4, 1942

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MINUTES, GENERAL ASSEMBLIES AND SECTIONS

BUSINESS SESSION

The Business Session of the General Assembly of the American Geophysical Union was held at noon on Friday, April 3, 1942, in Room 202 of the Hall of Government of George Washington University, Washington, D. C. The Session was called to order by President W. C. LOWDERMILK with a registered attendance of 35 members [see Appendix A].

The minutes of the General Assembly of the Twenty-Second Annual Meeting on May 2, 1941, had been published in the Transactions of 1941 and distributed to all members. They were approved as published.

The annual report of the General Secretary [see Appendix B] was summarized briefly, accepted with thanks, and ordered printed in full in the Transactions of 1942.

Reports of Standing Committees

Chairman MUSGRAVE'S report of the Committee on Membership is printed in full in Appendix C.

The report of the work of the Committee on Statutes and By-Laws, presented by Chairman HARRADON, is given in Appendix D.

Chairman SWICK of the Committee on Budget made no report, since the Union's fiscal year begins on July 1 and it was too far in advance of that date to propose a budget.

Chairman STETSON of the Committee on Meetings made no formal report, preferring to let the sessions of the Twenty-Third Annual Meeting serve as evidence of the Committee's activities. He expressed particular appreciation for the work of Vice-Chairman MARBLE on this Committee.

Chairman FLEMING of the Editorial and Publication Committee paraphrased Dr. STETSON'S remarks, and let the Transactions of 1941 speak for themselves.

Reports of Special Committees

The report of Chairman DISNEY for the Special Committee on Cooperation with International Commission for Study of Tidal Waves is given in Appendix E.

In the absence of Chairman HESS of the Special Committee on Geophysical and Geological Study of Oceanic Basins, Dr. THOM of the Committee stated that, because of the assignment of the Chairman to National-Defense duties, the report of the Committee's activities must be postponed.

Chairman Thom of the Committee on Geophysical and Geological Study of Continents reported that the same lines of activities as in the past had been followed but on a reduced scale because of the preoccupation of members in confidential investigations. The brief detailed report is given in Appendix F.

Chairman McCOMB read the report for the Committee on Time-Signal Service [see Appendix G].

Chairman STETSON of the Committee on Cosmic-Terrestrial Relationships stated that several projects of the Committee had proved helpful to Government agencies but that this year's report [see Appendix H] had necessarily to be curtailed because of its relation to the work of the National Defense Research Committee.

In the absence of Chairman FIELD of the Committee on National Welfare and Related Functions, Dr. THOM summarized the written report [see Appendix I]. He noted in particular that the proposals of the Committee concern activities bearing on the present emergency and on continuity of the Union looking toward demands of the future in national and international interests.

The Committee on Resolutions [J. MARBLE, N. H. HECK, and O. W. TORRESON] submitted through Chairman MARBLE a report recommending adoption of two resolutions which, after discussion, were unanimously adopted as follows:

Resolutions

(1) RESOLUTION ON RADIO TIME-SIGNAL SERVICE MAINTAINED BY THE UNITED STATES NAVAL OBSERVATORY AND THE NAVAL COMMUNICATION SERVICE

WHEREAS, The science of seismology, the operation of seismological stations, the science of geodesy, and many other activities of the American Geophysical Union and of all workers in geophysical science have a vital need of an accurate time-service, therefore be it

RESOLVED, That the American Geophysical Union again express its gratification for the radio time-signal service maintained by the United States Naval Observatory and the Naval Communication Service, which time-signal service has been of great aid in seismology and other branches of geophysics, and be it further

RESOLVED, That copies of this resolution be sent to the Secretary of the Navy, the Director of the Naval Communication Service, and the Superintendent of the United States Naval Observatory.

(2) RESOLUTION OF THANKS TO GEORGE WASHINGTON UNIVERSITY

RESOLVED, That the American Geophysical Union express its heartiest thanks to the authorities of the George Washington University for the courteous extension of their facilities to the Union for its Twenty-Third Annual Meeting and in particular to President CLOYD HECK MARVIN and Business Manager CHARLES E. MERRY, and be it further

RESOLVED, That copies of this resolution be forwarded to these gentlemen by the General Secretary of the American Geophysical Union.

The Committee also stated that a third resolution was to be submitted at the meeting of the Section of Hydrology on April 4, 1942; it was voted that any further resolutions which might be submitted by Sections which had not yet met in business session should, upon approval of the President and General Secretary, be sent to the Executive Committee for completion. In accordance with this action and with the approval of the Executive Committee of the Union at its meeting of September 18, 1942, resolution (3) was approved as follows:

(3) RESOLUTION TO INSURE CONTINUITY OF ESSENTIAL HYDROLOGIC RECORDS

WHEREAS, Uninterrupted hydrologic records, especially of precipitation, stream-flow, and ground-water supplies, are essential to the economic development, operation, and maintenance of public and industrial water-supplies, water-power plants, transportation-facilities, and river-control works, and to the administration in the public interest of the limited supplies of surface- and ground-waters, and, therefore, to local, regional, and national stability, be it

RESOLVED, That the American Geophysical Union urge that, for the war and post-war needs, provision should be made for insuring the continuity of these essential records, and be it further

RESOLVED, That a copy of this resolution be sent to the President of the United States, to the chairmen of the Appropriations Committees of the Senate and House of Representatives of Congress, and to the Governors of the several States.

Elections

The request of President ADAMS of the Section of Tectonophysics that approval of the General Assembly be given to incorporate in the meeting's business the action of the Section at its session later on April 3, 1942, to fill the office of Secretary of that Section, now left vacant by the resignation of DAVID GRIGGS, was granted. [See minutes of that Section, p. 733.]

The General Secretary reported that the Section of Seismology had elected A. BLAKE as Secretary for the three-year term beginning July 1, 1942, and that the Section of Hydrology had elected officers for the same three-year term as follows: President, J. E. CHURCH; Vice-President, LORENZ G. STRAUB; Secretary, K. HILDING BEIJ.

New business

The General Secretary submitted for discussion the question of possible affiliation of various Snow-Conferences (Western Interstate, North Central States, and Eastern) with the Union. Should these Conferences actively add to the membership of the Union, consideration might be given to

incorporating their proceedings in the Transactions without cost to them. The Western Interstate Snow-Survey Conference has paid the cost of preparing its material for publication in the Transactions. The question of affiliation of the Conferences with the Union was referred by the General Assembly to the Executive Committee for action.

The meeting was adjourned at 12:55 p.m.

EVENING GENERAL ASSEMBLY

The General Assembly for the Fourth Award of the William Bowie Medal, the Presidential Address, and the Illustrated Lecture on a Geophysical Subject was held in Room 1 of the Hall of Government of the George Washington University beginning at 8 p.m., April 3, 1942. An account of the Award and of the Address and Lecture is given on pages 179-183.

SESSIONS OF SECTIONS

The minutes of the meetings of the Sections of the American Geophysical Union, April 3 and 4, 1942, are given in Appendices J-a to J-h.

J. A. FLEMING, General Secretary,
American Geophysical Union

APPENDIX A--RECORD OF 372 MEMBERS AND GUESTS WHO REGISTERED ATTENDANCE AT THE GENERAL ASSEMBLY OF THE UNION AND AT SESSIONS OF ITS SECTIONS, TWENTY-THIRD ANNUAL MEETING, APRIL 3 AND 4, 1942

(Total number in attendance was considerably in excess of those registered)

(1 = Business session of General Assembly; 2 = Scientific session of General Assembly; a = Geodesy; b = Seismology; c = Meteorology; d = Terrestrial Magnetism and Electricity; e = Oceanography; f = Volcanology; g = Hydrology; and h = Tectonophysics)

Ackermann, R. F. (a,c)
Adams, L. H. (1,b,f,h)
Adams, Oscar S. (2,a)
Aitken, Janet M. (f)
Aldredge, R. C. (c)
Allen, Alice S. (f)
Allen, Roger A. (2,c)
Anderson, N. G. (c)
Arctowski, Henryk (2,c)
Arford, Carroll W. (c)
Aslakson, Carl I. (a,e)
Axtell, George C., Jr. (c)

Baker, Roger C. (g)
Baldwin, D. H. (a)
Balk, Robert (f)
Balsam, Ella (d)
Banks, Earl (c)
Barck, Wm. F. (a)
Barker, H. F., Jr. (c)
Baughman, Fred A. (c)
Beadbard, Samuel (c)
Beij, K. H. (2,g)
Bennion, V. R. (g)
Bernard, Merrill (g)
Bernstein, Arthur (d)
Bernstein, David (c)
Berry, F. A., Jr. (c)
Betz, Frederick, Jr. (2,a)
Blake, Archie (1,2,b)
Blanc, Milton L. (c)
Blazek, Harry J. (g)
Bleisdell, Fred W. (g)
Blythe, Richard H., Jr. (2,c,g)
Bodle, R. R. (a,b)
Bohenrer, J. H. (a)
Bollay, Eugene (c)
Borth, Blake B. (c)
Braaten, Norman F. (a)
Brancato, G. N. (c,g)
Brier, Glenn W. (a,b,c,d,g)
Brock, J. W. (c)
Brooks, Charles F. (c)
Brown, Carl B. (g)
Brune, Gunnar M. (g)
Bucher, Walter H. (f,h)
Buddington, A. F. (f,h)
Burbank, W. S. (f,h)
Burfell, Vincent S. (a)
Burwell, Edward B., Jr. (f,g)
Butow, Ernest E. (c)

Caldwell, R. M. (c)
Cannon, Ralph S., Jr. (f,h)
Capello, Jas. J. (1,2,d,e)
Carlin, A. V. (c)
Cartwright, G. D. (c)
Chandler, R. A. (c)
Chernosky, Edwin J. (b,c,d)
Clarke-Hafstad, Mrs. K. (c,g)
Clifford, Charles J. (a)
Cloos, Ernst (f,h)
Coats, Robert R. (f)
Cochran, A. L. (g)
Collins, W. D. (g)
Connaughton, Mark P. (g)
Conover, L. F. (c,g)
Corwin, Leonard B. (c,g)
Cotton, Harold A. (d)
Cudworth, E. T. (e)
Culley, F. L. (a)
Cunney, Geo. A., Jr. (a,d)

Darrow, Warren E. (e,g)
Davenport, R. W. (g)
Deel, S. A. (d)
Demorest, Max (c,e,g,h)
Devine, C. F. (e)
Diebold, C. H. (g)
Dimon, J. T. (c)
Disney, L. P. (1,2,e)
Disterdick, F. L. (c)
Dobson, G. C. (g)
Dorney, Margaret (c)
Dorsey, Herbert Grove (e)
Dorsey, Herbert P., Jr. (c)
Dove, W. N. (d)
Drane, Brent S. (c,g)
Duerksen, J. A. (2,a,b)
Dyck, Homer D. (c)

Ehrlich, Blake (c)
Eisenlohr, Wm. S., Jr. (g)
Elsner, Robert W. (c)
Escoffier, Francis F. (c,e,g)
Evans, L. B. (c)

Fahey, Jos. J. (f)
Faust, George T. (f,h)
Fellows, Robert E. (f)
Fiedler, Albert G. (2,g)
Finnigan, O. D., Jr. (c)
Fischer, R. P. (f,h)
Fisher, Bernard (f)
Fleischer, Michael (f)
Fleming, Jno. A. (1,2,a,b,c,d,e,g)
Fleming, Richard H. (e)
Fletcher, Peter W. (g)
Francis, W. J., Jr. (c)
Francis, William A., Jr. (d)
Fritz, S. (c)

Galpin, S. L. (g)
Galtsoff, Paul S. (e)
Gardner, Irvine C. (a,d)
Garner, C. L. (1,2,a,e)
Garstens, Martin A. (c)
Gault, H. Richard (f,h)
Gilliland, Theodore R. (d)
Gish, O. H. (1,2,c,d,f,g,h)
Glass, Jewell J. (f)
Goddard, E. N. (f)
Gold, Harold K. (c,g)
Goldman, Marcus I. (f,h)
Goodridge, R. S. (g)
Gorman, J. W. (e)
Grabski, Frank (g)
Graton, L. C. (f,h)
Green, J. W. (d)
Griggs, Robert F. (2,f)
Grover, N. C. (1,g,h)
Groves, George M. (c)
Gumbel, Emil J. (g)
Gunn, Ross (d,h)

Hagen, Norman R. (c)
Halstead, M. H. (c)
Haney, Mrs. Grace K. (1,d)
Harradon, Mrs. Amy A. (2)
Harradon, H. D. (1,2,c,d,e)
Harrison, Louis P. (c)
Harrold, John C. (e,g)
Hartung, James E. (c)
Hathaway, Gail A. (g)
Haurwitz, B. (c,e)
Hawley, J. H. (e)
Haynes, B. C. (c)
Heck, N. H. (1,2,b,d,e)
Heilprin, L. B. (d)
Hemple, H. W. (a,e)
Hendricks, G. E. (c)
Hendrix, William C. (d)
Henry, Thomas R. (c,d)
Hershberger, John (d)
Hertzler, R. A. (1,g)
Hickley, T. J. (a)
Holzman, B. G. (c,g,h)
Hoover, Marvin D. (g)
Horton, A. H. (g)
Horton, Robert E. (g)
Hough, Floyd W. (a,b)
Howard, C. S. (g)

Howe, H. H. (d)
Hoyt, William G. (g)
Huddleston, Thomas C. (a)
Humphreys, W. J. (c)
Hunter, Marvin N. (c)
Hurley, John (c)
Hursh, Charles R. (g)

Ingerson, Earl (1,2,f,h)
Ireland, Andrew T. (b,c)
Ireland, H. A. (g)
Izzard, Carl F. (g)

Jacob, C. E. (g,h)
Jahns, Richard H. (f,g,h)
Jarvis, Clarence S. (2,c,g)
Jennings, Arthur H. (c)
Jensen, Einar (f)
Jensen, Mrs. E. (f)
Joerg, W. L. G. (a,c,e)
Johnson, Joe W. (c,g)
Johnston, H. F. (1,2,c,d,e)
Jolliffe, A. W. (2,f,h)
Jones, P. R. (c)
Judson, Lewis V. (1,2,a,b,e)

Kaplan, Jacob (d)
Kazmann, Raphael G. (g)
Kelly, Sherwin F. (1,2,a,b,d,f,h)
Kennedy, Edward J. (g)
Kesler, Thomas L. (f,h)
Kiefer, P. J. (c)
Kincer, J. B. (c,g)
Kirkham, Don (g)
Knapp, David G. (d)
Kohler, J. P. (c)
Koschmann, A. H. (f,h)
Kyle, Jerry R. (a)
Kyler, M. W. (c,g)

Ladd, Robert Boyd (c)
Lambert, Walter D. (1,a,b,h)
Landsberg, H. (b,c)
Langbein, W. B. (c,g)
Lange, Isabelle (d)
Lassen, Leon (g)
Lee, F. W. (b)
Leifson, G. (e)
Leighly, John B. (c,e,g)
Lemke, Richard W. (f)
Lesher, Amy D. (c)
Leslie, H. K. (c)
Lieberman, Eva (c)
Light, Phillip (c,g)
List, Robert J. (c)
Little, D. M. (c)
Lloyd, J. R. (c)
Lobell, Milton J. (e)
Longwell, C. R. (1,2,a,b,e,f,h)
Lorz, John G. (d,e,f)
Louthen, Willard V. (c)
Love, S. Kenneth (2,g)
Lovering, T. S. (f,h)
Lowdermilk, W. C. (1,2,b,c,d,e,g)
Ludy, A. K. (b,d)
Lynott, Wm. J. (f)

MacNeal, J. Neal (d)
Malkin, William (c)
Maples, H. M. (c)
Marble, John Putnam (1,2,f,h)
Marble, Mrs. A. H. (e,f,h)
Marmer, H. A. (e)
Mason, Martin A. (e,g)
Matthes, François E. (g)
Mattice, W. A. (c,g)
Maxwell, John C. (f,h)
Mayhew, H. B. (a,e)
Maynard, R. H. (c)
McAllister, J. F. (f)
McCarthy, Daniel V. (g)
McComb, H. E. (1,2,b,d)
McCurdy, P. G. (e)
McKnight, Edwin T. (f)
Meinzer, O. E. (1,2,f,g,h)
Merriam, Carroll F. (a,g)
Mitchell, C. L. (c)
Mitchell, Hugh C. (a)
Mohl, E. V. (a,e,f,g,h)
Murphy, Leonard M. (b)
Murphy, Robert Cushman (1,2,e)
Musgrave, Geo. W. (1,2,b,g)

Namias, Jerome (c)
Nelson, John M. (f)
Neumann, Frank (b,d,h)
Norton, Horace W. (b,c,g)

O'Connell, D. T. (1,2,b,c,e,f,g,h)
O'Connell, Mrs. Daniel T. (2)
Olmstead, L. B. (g)
Olson, J. C. (f)
Ostrow, Sidney M. (d)
Owen, J. C. (c,g)

Page, B. L. (a)
Pallister, Darthula (c)
Parker, Nathan O. (2,a,d,g)
Parkin, Ernest J. (a)
Parrish, R. M. (c)
Parsons, Willard H. (2,f,h)
Pate, Elbert W. (c,e)
Pear, C. B., Jr. (c)
Peavey, R. C. (d)
Pegelow, Frederic G. (c)
Penne, Harold (c)
Peter, Hollis W. (c,g)
Peterson, B. J. (g)
Phair, George (f)
Phillips, Mrs. J. F. (c,d)
Pickard, R. W. (d)
Puffer, Shirley (2,d)
Pugh, David D. (a)

Rampey, Ernest M. (c)
Ramser, C. E. (g)
Rappleye, Howard S. (2,a)
Ripamonte, Carlos E. (b)
Robertson, James M. (g)
Roman, Irwin (1,2,a,b,d,f,h)
Roquemore, W. P. (c)
Ross, Clarence S. (f)
Rosseland, Svein (c,d)
Rothrock, H. I. (c)
Rounsefell, John N., Jr. (a)
Rubey, William W. (f,g,h)
Rupp, Russell D. (c)

Sarle, Chas. F. (c)
Schaller, W. T. (f)
Schmitt, Waldo L. (1,2,e)
Scofield, La Mont (c)
Scott, Walter E. (c,d,e,g)
Seamon, Lilburn H. (c)
Seiwell, H. R. (c,e)
Sharp, A. L. (g)
Sharpe, C. F. Stewart (c,f,g,h)
Shepard, E. R. (b)
Sherman, K. L. (1,c,d,h)
Shofnos, William (a)
Showalter, Albert K. (c,g)
Silsbee, F. B. (d)
Silsbee, Mrs. Francis B. (d)
Silsbee, H. B. (2,d)
Simmonds, Thos. H. (c)
Singewald, Joseph T., Jr. (f)
Small, James B. (a)
Smith Ed. H. (e)
Smith, Forrest E. (1,2,e)
Smith, Lorine A. (a,e,f)
Smith, Newbern (d)
Smith, Richard M. (g)
Smith, Waldo E. (1,c,g)
Snyder, Franklin F. (c,g)
Sohon, F. W. (b)
Sollenberger, Lucy W. (a)
Solot, Samuel B. (c)
Solter, Christie J. (f)
Soroka, Mary O. (g)
Southwick, Thos. S. (c)
Southworth, Jay L. (g)
Spencer, Arthur C. (b,g)
Spengler, Kenneth C. (c)
Spicer, H. Cecil (d,f,h)
Spilhaus, A. F. (c,e)
Staring, Merlin H. (d)
Staudte, Curtis E. (a,h)
Stechschulte, V. C. (2,a,b)
Steenland, N. C. (b,d,h)
Stephenson, Robert C. (2,f)
Stetson, Harlan T. (1,2,c,d,h)
Stevens, Rollin E. (f)
Stevlingson, D. J. (c)
Stodghill, W. E. (c,g)
Stose, Anna Jonas (2,f)
Stose, George W. (f)
Stow, Marcellus H. (f,h)
Sutcliffe, Walter D. (2,a)
Swainson, O. W. (2,b,d,e)
Swartz, J. H. (b,d,f,g)
Swenson, Bennett (c,g)
Swick, C. H. (1,2,a,e,h)

Thom, W. T., Jr. (1,2,a,d,f,h)
Thompson, David G. (g)
Thornthwaite, C. W. (1,2,c,g)
Trade, H. F. (c)
Trask, Parker D. (e,g,h)
Truesdell, Page E. (a,h)
Turner, Lewis M. (g)

Varnes, D. J. (g)
Vestine, E. H. (d,h)
Vhay, John S. (f)

Wait, G. R. (c,d)
Wallis, Wm. F. (c,d)
Walters, J. F. (c)
Warfield, Richard (b)
Wayland, R. G. (f)
Weightman, R. H. (c)
Weisbord, Norman E. (a)
Wells, H. W. (b,c,d)
Wexler, Harry (c)
Whitcroft, Thos H. (e)
White, Ralph Herbert (c)
Whitmore, D. R. E. (f)
Whitney, Paul C. (e)
Wiggin, B. L. (c)
Wiles, William E. (d)
Willard, Max E. (f,g,h)
Williamson, Philip H. (d)
Wilson, James T. (b,h)
Wilson, Ralph N. (c,g)
Wilson, Raymond H., Jr. (c)
Wilson, Ronald M. (1,2,a)
Wilson, Walter T. (g)
Winner, John P. (c)
Witt, E. J. (e)
Woodside, Roy H. (2)

APPENDIX B--REPORT OF THE GENERAL SECRETARY OF THE AMERICAN GEOPHYSICAL UNION TO THE GENERAL ASSEMBLY, TWENTY-THIRD ANNUAL MEETING, APRIL 3, 1942

Minutes of the Twenty-Second Annual Meeting on May 2, 1941, appear on pages 567 to 569 of the Transactions of 1941, which were distributed to all members of the Union and to authors of papers presented at the meeting. There have been received no suggestions for changes or corrections.

Since the last annual meeting, we have learned of the death of nine members: CLAUDE H. BIRDSEYE, May 30, 1941, affiliated with the Sections of Geodesy and Volcanology; W. C. DEVEREAUX, July 6, 1941, affiliated with the Sections of Meteorology and Hydrology; E. W. EICKELBERG, May 21, 1941, affiliated with the Sections of Geodesy, Seismology, Terrestrial Magnetism and Electricity, Oceanography, and Tectonophysics; C. C. ENNIS, November 24, 1941, affiliated with the Sections of Meteorology, Terrestrial Magnetism and Electricity, and Oceanography; GEORGE M. HALL, April 28, 1941, affiliated with the Section of Hydrology; L. J. HENDERSON, February 10, 1942, Ex-Officio Member, Chairman of the Division of Foreign Relations of the National Research Council; GLENN W. HOLMES, January 1940, affiliated with the Sections of Meteorology and Hydrology; D. A. LANE, July 1, 1941, affiliated with the Sections of Seismology, Meteorology, and Hydrology; H. R. LEACH, June 24, 1941, affiliated with the Sections of Meteorology and Hydrology.

The total membership of the Union April 1, 1942, is 1504--a net gain of 177 since the last annual meeting. The Membership Committee expects to continue its campaign for new members through the registration of guests at all meetings of the Union and through the circulation of Union literature to qualified lists of prospects.

After checking addresses, Section affiliations, etc., by circulating reply cards, a list of members and officers of the Union as of February 15, 1942, was prepared and printed in an edition of 2000 and distributed to the entire membership, together with program of the Twenty-Third Annual Meeting and the revised Statutes and By-Laws.

The Executive Committee has met three times since the last annual meeting (June 21 and November 14, 1941, and February 20, 1942). Minutes of these meetings have been distributed to the Committee and to officers of the Sections.

The Twenty-Third Annual Meeting of the Union and its Sections was arranged for in the Hall of Government of George Washington University for April 3 and 4, 1942. Despite the curtailed schedule, the program for scientific sessions includes 104 papers and progress-reports.

In accord with established practice and the approval of the Executive Committee, the President appointed Standing and Special Committees for the year 1941-42 as listed on pages 28 and 29 of the List of Members and Officers. In addition there was designated the Committee on Resolutions for the Twenty-Third Annual Meeting, as follows: J. P. MARBLE, Chairman; N. H. HECK, and O. W. TORRESON.

The Transactions of 1941 consisted of three parts, totaling 1036 pages (equivalent to 1500 pages in ordinary printer's format): Part I containing reports and papers of the Joint Regional Meeting of the South Pacific Coast Area of the Section of Hydrology and the Western Interstate Snow-Survey Conference at Sacramento, California, in January, 1941; Part II (368 pages) giving

the proceedings of the General Assembly and all Sections except Hydrology at the Twenty-Second Annual Meeting; and Part III (452 pages) which includes the complete proceedings of the Section of Hydrology at the Twenty-Second Annual Meeting. Despite the increased cost of paper and labor, the total cost of preparing and printing the Transactions of 1941 for an edition of 2000 was $3221.39--an average of $1.61 per set or $3.10 per page for the whole edition. In addition to this regular edition of 2000 there were also printed 2600 copies of Part I for sale to the Western Interstate Snow-Survey Conference and 200 copies of Part III to meet the larger demand for hydrologic papers. The editing, preparing of copy, printing, and distribution of last year's Transactions was completed in October. As in past years, complete sets were sent not only to members and authors, but also to libraries and scientific review organizations.

During the year there have been three well-attended regional meetings sponsored jointly by the Union and other societies: The Hydrology Conference at State College, Pennsylvania, June 30 to July 2, 1941, under the joint auspices of the Section of Hydrology, the Civil Engineering Division of the Society for the Promotion of Engineering Education, the Committee on Hydrology of the American Society of Civil Engineers, and the Pennsylvania State College, at which there were more than 230 persons attending; a joint session with Section E of the American Association for the Advancement of Science, the Texas Academy of Science, Dallas Petroleum Geologists, and Fort Worth Geological Society on the afternoon of December 30, 1941, at Dallas, Texas, at which eight papers were presented; South Pacific Meeting, Section of Hydrology, and the Western Interstate Snow-Survey Conference at Pasadena, California, January 16 and 17, 1942, where 13 papers were presented in one afternoon and two morning sessions and a motion picture of Swiss avalanches, round-table report of forecasters, a lecture on snow-survey equipment, followed by discussion and business session, formed an interesting program at an evening dinner meeting of the Western Interstate Snow-Survey Conference jointly with the Section of Hydrology. The papers presented at Dallas, Texas, are being prepared for publication in the Transactions of 1942. Because of the relatively short program of the Western Interstate Snow-Survey Conference, it has been authorized by the Executive Committee that, except for reprints, the proceedings of that Conference be included in the Transactions without cost to the Conference.

The second meeting of the Eastern Snow Conference was held at Albany, New York, September 8, 1941, and a final report of the Research Committee of 1940-41 of the Conference was received from C. F. MERRIAM, Chairman of that Committee. WALTER T. WILSON succeeds C. F. MERRIAM as Chairman for next year.

A successful and well-attended meeting in which the Union took part was the Central Snow Conference at East Lansing, Michigan, December 11 and 12, 1941; following numerous papers and discussions presented during five morning and afternoon sessions, an informal banquet was held December 11, 1941, at which a brief business session was followed by a statement on "Hydrologic activities of the American Geophysical Union in relation to snow" and an address "Looking ahead." G. W. MUSGRAVE, Chairman of the Membership Committee, attended this Conference and found great interest there in the American Geophysical Union. The papers submitted at the Conference will be printed by Michigan State College.

The Bibliography of Hydrology, United States of America, for the year 1940 (93 pages) was prepared in the usual edition of 1000 from manuscript prepared by the Secretary of the Section of Hydrology and the Committee on the Bibliography. Four hundred copies each of this and of the edition for 1939 are being held as required for the Secretary of the International Association of Scientific Hydrology and the sale of the remaining supply continues at the rate of $0.85 per copy (prepaid, pre-publication price was $0.60 per copy).

The three-year terms of R. M. FIELD and N. H. HECK on the Division of Foreign Relations of the National Research Council expired June 30, 1941. Since the Executive Secretary of the Council advised there was no restriction on the number of members from the American Geophysical Union in that Division, W. C. LOWDERMILK, President of the Union, and FIELD and HECK were appointed members of the Division representing the Union during July 1, 1941, to June 30, 1944. Membership of the Union on this Division is now N. C. GROVER, R. M. FIELD, J. A. FLEMING, N. H. HECK, C. O. ISELIN, W. C. LOWDERMILK, and T. G. THOMPSON.

Replying to the invitation of the President, Trustees, and faculties of Fordham University to have a delegate of the Union attend the celebration of the centenary of that University on September 15, 16, and 17, 1941, the President appointed Rev. J. B. MACELWANE as official delegate of the Union.

The Section of Seismology of the Union and the Eastern Section of the Seismological Society

of America designated T. J. ETHERINGTON, resident in Bogotá, to represent both organizations at the dedication of the new seismological station at Bogotá, Colombia.

Following a request received from the Geophysical Education Committee of the American Institute of Mining and Metallurgical Engineers, held in New York February 9, President LOWDERMILK appointed as special delegates to represent the Union at this meeting R. M. FIELD, A. F. BUDDINGTON, WALTER H. BUCHER, and J. T. WILSON.

In accordance with the action of the Executive Committee, a circular letter under date of December 1, 1941, showing changes in Statutes and By-Laws proposed by the Executive Committee as a result of the report of its Committee on Statutes and By-Laws, was mailed to all members of the Union with request that votes on the various proposed changes be submitted by December 31, 1941. Total number of ballots received was 482 and votes were overwhelmingly "yes" for each of the proposed changes. Authorization was given for printing of the revised Statutes and By-Laws and these, as stated above, have been mailed to the members.

The report of the Auditing Committee for the calendar year 1941 showed that the records of receipts ($15,653.25, including balance January 1, 1941, of $6511.97) and disbursements ($9644.91) were correct.

The Chairman of the National Research Council, in his report concerning the activities of the Council, advises that it is expected that the usual allotments for international dues will be made for four of the organizations which have deposits of funds in this country, namely, the International Council of Scientific Unions, the International Union of Geodesy and Geophysics, the International Union of Astronomy, and the International Scientific Radio Union. The balance in the account of the International Union of Geodesy and Geophysics with Riggs National Bank is $6,731.22.

Arrangements were effected by the General Secretary to receive through the Swiss Legation for the Chairman of the International Commission on Snow the avalanche film which had been made at the expense of that Commission for instructional purposes in the United States. This film was received in January and has been presented at various meetings throughout the country.

Reimbursements of $300 to each of three donors (Carnegie Corporation of New York, National Research Council, and Geological Society of America) were made from balance of funds for the Washington Assembly of 1939 in accordance with the action of Executive Committee on June 21, 1941, and appreciative letters were received from each.

In accord with General Winterbotham's advice reported last year, 400 printed copies of the General Transactions of the Washington Assembly (1939) were forwarded and have been distributed to those who had requested them. A bill has been received for 375 copies of the Transactions of the Association of Seismology from Secretary Rothé in a total of 3,620.85 francs (equivalent to about $90), and he has been asked to forward these by post in a number of separate packages. Thus there still remain to be published the Transactions for the Associations of Geodesy, Volcanology, and Scientific Hydrology. For such publication the Executive Committee has authorized the following apportionments of Washington Assembly balances: Seismology, $90; Scientific Hydrology, $1000; Volcanology, $300; Geodesy, $250.

Upon request of the Economic Defense Board, a statement on behalf of the American Geophysical Union was submitted showing the objects of the Union, the constitution of its Executive Committee, a statement of the acts of Congress on adherence of the United States to the International Council of Scientific Unions and Associated Unions, and a corrected copy of the address list of members of the Union.

The Executive Committee voted to suppor lthe resolution of the American Astronomical Society at its meeting of December 29, 1941, for continuance of latitude observations sponsored by the International Astronomical Union and the Association of Geodesy of the International Union of Geodesy and Geophysics.

The year's record is one of increasing coordination and collaboration, especially with the geophysicists of the whole Western Hemisphere, to preserve and protect for the future those international relations so necessary to investigations of earth-physics.

J. A. FLEMING, General Secretary,
American Geophysical Union

APPENDIX C--REPORT OF COMMITTEE ON MEMBERSHIP

The Committee on Membership consists of Messrs. BLAKE, DISNEY, JOHNSTON, LITTLE, MUSGRAVE, RAPPLEYE, RUBEY (resigned March 12, 1942, because of necessity of being in the field), and VHAY, each Section of the Union having one representative on it. Following instructions of the Executive Committee it has been busily engaged in attempting to interest many workers in the Union and its activities and to expand the membership. In this work the advice and tangible assistance of many officers and numerous members throughout the country has been a source of real stimulation. It is impracticable to list in detail the very large numbers of individuals who have been the primary means of securing not merely one or two new members but to whom, as in several instances, as many as 35 new members may be traced. This is exclusive of the effect of the letter of the President to the membership of the Union which resulted in an immediate and inspiring flow of proposal forms. Between January 16, when the first response to the letter was received, and March 31, 1942, 196 proposals were received.

These new members had an average affiliation of one and two-thirds sections per member and the percentage gain in membership by Sections was as follows:

Section	Gain in per cent	Section	Gain in per cent
(a) Geodesy	8.4	(e) Oceanography	7.6
(b) Seismology	7.6	(f) Volcanology	5.3
(c) Meteorology	14.5	(g) Hydrology	16.3
(d) Terrestrial Magnetism and Electricity	10.9	(h) Tectonophysics	8.4

Expenditures of the Committee (largely for form-letters and postage) total $120.63.

The War Effort of the Nation undoubtedly has its effect upon this membership activity but it should only serve to spur us on to further endeavors. In nearly every Section of the Union, specialized mailing lists of prospective members are being utilized; at each regional meeting a list of non-members registering attendance is assembled and even the new members are to be asked to step into the harness for the united effort. Let me suggest that when writing a colleague on any matter it is very easy to slip into the same envelope a proposal-for-membership form on which you have written his name and signed your own as sponsor. If you do nothing more than this, a very large percentage will be returned as completed forms. A supply of proposal forms can be obtained from any member of the Committee or from the office of the General Secretary.

If we contact 4,500 prospects we should easily obtain 1,500 members. In this we need the help of every one.

G. W. MUSGRAVE, Chairman

APPENDIX D--REPORT OF THE COMMITTEE ON STATUTES AND BY-LAWS

Several important changes have been made in the Statutes and By-Laws of the Union during the past year. At its meeting on June 21, 1941, the Executive Committee instructed the Committee on Statutes and By-Laws to recommend an amendment by which members in good standing for a given number of years should be extended the complete privileges of active membership from date of retirement from service without further payment of dues. Such a statute was prepared and received the approval of the Executive Committee at its meeting of November 14, 1941.

At the meeting of the Executive Committee of November 14, 1941, it was voted, on the recommendation of the Committee on Membership, to create a new class of members known as associates and to make various changes in the Statutes pertaining to the other classes of membership. The required Statutes were drawn up and together with the Statute regarding retirement, mentioned above, were submitted to the members of the Union by the General Secretary for a mail vote under date of December 1, 1941.

All these proposed changes in the Statutes were approved by a large majority of the members of the Union and have been duly incorporated in the latest version of the Statutes and By-Laws, as amended to February 20, 1942.

H. D. HARRADON, Chairman

APPENDIX E--REPORT OF SPECIAL COMMITTEE FOR COOPERATION WITH INTERNATIONAL COMMISSION FOR STUDY OF TIDAL WAVES

The following information has been collected relative to seismic disturbances off the coast of Costa Rica on December 5 and 6, 1941, and storm-tides along the Atlantic coast of the United States on March 1-3, 1942.

Seismic seiche--On the basis of instrumental reports, an earthquake occurred off the coasts of Costa Rica and Panama at $14^h\ 46.8^m$, 90° west meridian time on December 5, 1941, with location of epicenter approximately 8° north latitude, 83° west longitude, with an aftershock occurring at $15^h\ 24.6^m$, 90° west meridian time on December 6, 1941, in the same location.

Seiches set up by these earthquakes are clearly indicated on the marigram from the tide-station at Puntarenas, Costa Rica, maintained on a cooperative basis by the Republic of Costa Rica and the Coast and Geodetic Survey.

The first indication on the marigram of the shock of December 5 was at about $16^h\ 00^m$, 90° west meridian time. The disturbance is well defined until about $22^h\ 00^m$, the average period of the seiche being about 30 minutes with an average amplitude of approximately one foot.

The seiche set up by the aftershock on December 6, 1941, began at about $16^h\ 20^m$, 90° west meridian time, and continued until about $23^h\ 00^m$, the average period being about ten minutes and the average amplitude approximately one-half foot.

Storm-tide--The storm which originated in the Gulf of Mexico, near Corpus Christi, Texas, on March 1, 1942, and followed a path across the Gulf to the vicinity of Tallahasee, Florida, and then northward along the Atlantic coast approximately 100 miles inland, was attended by storm high tides followed by storm low tides on the coasts of the southern States and by storm high tides along the Middle Atlantic and New England coasts.

The variation in the height of the water-level at various places as derived from records at tide-stations maintained by the Coast and Geodetic Survey is given in Table 1.

Table 1

Station	Date	Time[a]	Height of high water above		Height of low water below	
			Mean high water	Predicted high water	Mean low water	Predicted low water
	1942	h	ft	ft	ft	ft
Galveston, Texas	Mar. 1	12.5	1.3	1.6	....	....
	2	11.0	....	....	2.6	2.1
Pensacola, Florida	2	1.7	0.6	1.0	....	....
	3	8.2	....	....	0.7	0.8
Charleston, South Carolina	2	7.7	1.4	1.2	....	....
	3	2.0	....	....	2.5	1.7
Wilmington, North Carolina	2	22.4	1.7	1.5	....	....
	4	6.5	....	....	0.9	0.7
Hampton Roads, Virginia	2	21.3	1.8	1.8	....	....
Philadelphia, Pennsylvania	3	14.1	2.4	1.9	....	....
New York, New York	3	8.5	3.0	2.7	....	....
New London, Connecticut	3	8.5	3.5	3.7	....	....
Newport, Rhode Island	3	8.1	3.1	2.9	....	....
Boston, Massachusetts	3	11.7	2.9	2.0	....	....
Portland, Maine	3	11.0	3.0	2.2	....	....

[a]The time for Galveston and Pensacola is 90° west meridian, and for other stations 75° west meridian.

L. P. DISNEY, Chairman

APPENDIX F--REPORT OF SPECIAL COMMITTEE ON GEOPHYSICAL AND GEOLOGICAL STUDY OF CONTINENTS

Activities relating to the geophysical and geological study of continents have been as follows:

First, the use of the Humble gravimeter, loaned by the Union to the Missouri Geological Survey, to establish about 2000 more stations in the parts of Missouri not previously covered. Thus the State now is crossed by a gird of gravity-traverses 15 to 20 miles apart, with stations at intervals of five or six miles along each traverse. Previous magnetometer-traverses had been made over this area, and interesting correlations are evident between the various geophysical results and the near-surface and subsurface geologic controls.

Second, receipt from the United States Coast and Geodetic Survey of the isostatic reductions for 50 gravity-meter stations along Dr. WOOLLARD'S magnetic and gravity profile from the Pacific to the Atlantic--for which the final report is now in process of publication by the Geological Society of America.

Third, Dr. WOOLLARD'S recent investigations in New Jersey, made during the time of his National Research Council and Guggenheim fellowships, have resulted in the publication of New Jersey Geological Survey Bulletin 54, "Geophysical investigations in New Jersey", and in the preparation of a report on the "Geologic correlations of areal gravitational and magnetic studies in New Jersey and vicinity"--also being prepared by the Geological Society of America for simultaneous publication with a similar paper by Professor LONGWELL of Yale giving a geological interpretation of gravitational data now accumulated for southern New England. Dr. WOOLLARD has recently gone to the Woods Hole Oceanographic Institute and has taken the gravimeter with him, planning to establish stations on Nantucket and Martha's Vineyard in the near future, and otherwise fill in as many gaps as possible in New England, before the weather becomes too cold for the thermal controls on the instrument.

The Committee has also been seeking light on how it and its members could best assist with the immediate emergencies of the War and with preparation for an optimum post-War situation. The emergency-disruptions have now largely fallen into pattern, and are being provided for in a reasonably comprehensive and effective way. The great problem remaining is to so arrange that geophysical and geodetic work after the War may go forward as rapidly and effectively as possible--partly for the sake of the scientific results to be achieved and partly in order to provide another basis of friendly and mutually helpful collaboration between nations which have been ravaged and shaken by the War.

The geophysical-geological problems of continents cannot be solved in one continent--nor can they be solved independently of the problems of the oceanic basins, or of the relations of the Earth to our universe. The Special Committee on Oceanic Basins will probably be perforce largely inactive during the War, but the Special Committees on Continents and on Cosmic-Terrestrial Relationships can undoubtedly do much work of value in the meanwhile, especially if the International Union's Commission on Continental and Oceanic Structure can be stimulated into keeping matters going from the International Union point of view, by arranging for collaborative work between the United States Committees and those of Canada at the outset, and those of Latin America, South Africa, and Australia-New Zealand as soon as possible. The same type of operations which have been carried on in the United States, if cooperatively extended to these other areas, will aid greatly in the advancement of geoscience per se, and will indirectly be of utmost value in indicating the geophysical and geological limiting factors which world-society must allow for in planning for the future.

With careful planning and broad cooperation, a great deal that is useful can be done, and it is our responsibility to do what we can to help get it done as soon as possible. The time is ripe for further regional geophysical-geological compilations, and for the stimulation of interest in the creation of world-wide systems of geophysical bench-marks and reference-stations.

W. T. THOM, JR., Chairman

APPENDIX G--REPORT OF SPECIAL COMMITTEE ON TIME-SIGNAL SERVICE

Your Committee has maintained contact with individuals and organizations that use Naval time-signals for various scientific purposes. It has supplied information to the Navy Department regarding the minimum requirements for these signals.

Because of the emergency, the Naval Communications Service has found it necessary to curtail very sharply the broadcasting of time-signals. Beginning on April 1, 1942, for example, only four regular signals will be transmitted from Annapolis, NSS, although these will be on several different frequencies. When the Committee learned that some curtailment would probably take place, it made a thorough canvass of the various scientific users in the American Geophysical Union to learn just what signals were most necessary. A list was then compiled and sent to the Secretary of the Union for transmittal to the Navy Department.

There can be no doubt that the curtailment of the time-service will be a serious loss and inconvenience to many members of the American Geophysical Union. It is recommended, however, that for the duration of the emergency requests for additional service be limited to indispensable requirements. If it is found that certain important scientific investigations cannot be carried out under the reduced schedule, your Time-Signal Committee should be notified and a detailed explanation furnished to show the imperative need for the additional service.

It should be noted that the decrease in service is due entirely to limitations of transmitting service caused by the War and that the Naval Observatory would continue the full schedule of peace-time broadcasts except for this limitation. During the coming summer, the Navy will transmit a special signal at 13^{h} GMT for use of an astronomical party of the United States Coast and Geodetic Survey working in Alaska.

H. E. McCOMB, Chairman

APPENDIX H--REPORT OF SPECIAL COMMITTEE ON COSMIC-TERRESTRIAL RELATIONSHIPS

Expediency on account of wartime restrictions necessitates a considerable abridgment in the report of the activities of this Committee during the past year.

In addition to the fact that many members have been devoting a major share of their time and effort to research of direct military value, the results of certain investigations of fundamental importance in communications must obviously be delayed in publication until a more appropriate occasion. It is gratifying to your Committee to be able to report that the field of cosmic-terrestrial relationships has proved itself to be one of increasing importance in the present emergency. Developments in this field for the last 20 years have been so important as to make of fundamental consequence observational data unavailable in the last war.

During 1941-42 solar activity has continued to decline as was expected in anticipation of the approaching minimum in 1943 or 1944. A considerable disturbance occurred in September giving rise to the Zurich index-number of 148 on September 17. This was accompanied by auroras, magnetic storms, and extended interruptions to radio communication. This proved to be the most violent outbreak since the Easter disturbance of 1940.

Captain Hellweg states that the Naval Observatory has continued to collect sunspot-data which have been made available to authorized sources. The report of the unusual conditions preceding the disturbance of September 17, 1941, proved of special value to the Government defense-agencies in anticipation of the disturbed communication conditions that were predicted and that were later fully realized.

This incident alone was of sufficient consequence to emphasize the importance of continuous solar observations and further research in the significant field of solar-terrestrial relationships. It is with considerable regret that due to the present exigencies the Naval Observatory time-signal broadcasts have had to be cut from the customary 24 times per day to four times per day. However, in addition to the four remaining sets of signals, other signals are sent from Mare Island on the Pacific Coast.

Captain HECK has communicated the following report for the United States Coast and Geodetic Survey from information furnished him by Commander SWAINSON, Chief of the Division of Geomagnetism and Seismology:

"(1) Cosmic-ray recording apparatus was operated by the personnel of the United States Coast and Geodetic Survey Magnetic Observatory at Cheltenham, Maryland, throughout the year. Records were forwarded to the Carnegie Institution of Washington for processing.

"(2) Telegrams giving notice of the beginning of magnetic storms were forwarded to Dr. T. H. JOHNSON of the Bartol Research Foundation, Swarthmore, Pennsylvania, and Dr. W. P. JESSE of the University of Chicago in order that these persons might send up balloons carrying cosmic-ray recording apparatus.

"(3) The United States Coast and Geodetic Survey sponsored a Work Projects Administration project in charge of Dr. G. W. KENRICK at San Juan, Puerto Rico, to make ionospheric observations at various radio frequencies. The data from the project were forwarded to Dr. DELLINGER of the National Bureau of Standards.

"(4) Atmospheric-electric observations were made in cooperation with the Department of Terrestrial Magnetism of the Carnegie Institution of Washington and Bell Telephone Laboratories at Tucson, Arizona.

"(5) K-numbers for the five observatories were furnished throughout the year though for the latter part of the year their publication has been discontinued and their use limited."

Dr. CHARLES F. BROOKS, Director of the Blue Hill Meteorological Observatory, writes the following report for such work as bears on the province of this Committee:

"The Blue Hill Meteorological Observatory, in cooperation with the United States Weather Bureau, has continued its continuous recording of the intensity of the direct radiation from the Sun on a normal surface and of the filtered direct radiation through SCHOTT filters OG-1 and RG-2, two of each about one hour apart on every clear morning. We are also continuing the record of total solar and sky radiation on a horizontal surface as received by an EPPLEY pyrheliometer. Both the direct radiation and the total radiation are recorded on a Leeds and Northrup micromax potentiometer.

"Our series of ultra-violet measurements with a chemical dosimeter came to an end in December when the instrument broke. Since that time we have not made any measurements of ultra-violet radiation ourselves, but the Weather Bureau Station at Blue Hill, I. F. HAND in charge, has been obtaining an actual automatic record of ultra-violet radiation through a filter. They have also been obtaining the infra-red radiation in the same manner.

"The Weather Bureau is obtaining a continuous record of sky-polarization in clear weather.

"Our observations of the aurora borealis are continuing without essential change. Jointly with H. T. STETSON, a summary of our aurora records from 1885 to 1940 was published in the Journal of Terrestrial Magnetism and Atmospheric Electricity [March, 1942].

"The present dimout, effective over the Boston Region, has reduced the sky-illumination so appreciably that during the remainder of the War we should be able to see faint auroras more readily than has been possible in recent years. On the other hand, increased industrial smoke will work adversely, though probably not to the extent that the lack of city lights will favor the observations.

"Some observations with the COBLENTZ type of ultra-violet meter, cadmium cell, have been made on Mt. Washington during the last two years, from time to time, but they have not as yet been reduced."

H. H. CLAYTON, cooperating in the field of meteorology, has continued his investigations relative to the magnetic K-indices published by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. He has found that in the averages of four years there was a lag of about one day in the daily maximum of sunspot-numbers and maxima in the K-indices determined at the seven widely separated observatories. He has found that the most frequent occurrence of maxima in the K-numbers came in general when large spots were near the central area of the Sun, although occasional outbreaks occurred when there were large spots distant from the central area. The most favorable conditions for large values of K occurred when there was an increase in solar activity coincidental with spots in the central area. Mr. CLAYTON found distinct evidence for the return of K-maxima at intervals of about 27.3 days. Longer intervals were interpreted to mean that the radiation responsible for magnetic disturbances, presumably corpuscular, occasionally came from latitudes higher than the mean latitude of the sunspots.

Mr. CLAYTON has also spent some time investigating any possible relation between the 11-year sunspot-period and annual spring rainfall. Dividing the United States into three sections, (1) Rocky Mountain States, (2) Central States between Missouri and the Dakotas, and (3) Atlantic States, the average of the last five sunspot-periods indicates an actual increase by more than 30 per cent in the rainfall over the Rocky Mountain Region and the Central States in passing from sunspot-minimum to sunspot-maximum; the inverse relation seemed to hold in the Atlantic Region, particularly in the South Atlantic States.

Mr. CLAYTON interprets these facts to mean an increase in the low-pressure normal for

spring in the Southern Rocky Mountain Region and an increase in the higher pressure normally over the Atlantic at that season. Such a change in the distribution of pressure, he believes, would tend to increase the circulation of rain-bearing winds west of the Mississippi River.

The Annual Report of Dr. JOHN A. FLEMING, Director of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, reveals that in spite of the large amount of time the staff is devoting to war work notable progress has been made in investigations of a fundamental character in geomagnetism and terrestrial electricity. Details of the great magnetic storms of March 24, 1940, and March 1, 1941, have contributed to a better understanding of changes in the upper atmosphere accompanying such storms and indicate that definite atmospheric movements may be associated with magnetic storms of the types indicated in these two major disturbances. It is now generally recognized that electrically charged corpuscles bombarding the Earth's atmosphere are deflected toward the polar regions as they enter the influence of the geomagnetic field. The resultant ionization of the high atmosphere in these regions where the Earth's field is nearly vertical in respect to the surface, appears to be the cause of auroras and current flowing in the atmosphere results in violent fluctuations in the geomagnetic field.

Dr. FLEMING stresses that the relationships of these phenomena and the distribution of the ionization in the polar regions present a problem the solution of which is not only of theoretical importance but of practical consideration because of the application to the problems of radio-wave propagation.

An investigation of the polar fields of sudden commencements of magnetic storms shows that the north component of a commencement diminishes and that the vertical component increases with increasing geomagnetic latitude in the region inside the auroral zone. Average values of the disturbing diurnal variation, the solar daily variation, daily means of disturbance and non-cyclic change for the international disturbed and quiet days have now been reduced for nearly all the stations of the Polar Year 1932-33.

The investigation of the relations of geomagnetic with solar, lunar, and other cosmic phenomena has been continued by BARTELS, CHAPMAN, and JOHNSTON.

The Report of the Committee on Coordination of Cosmic-Ray Investigations under the auspices of the Carnegie Institution of Washington for the year 1940-41 is in itself a contribution to the field of cosmic-terrestrial relationships. The fact that the present state of cosmic-ray investigations indicates the possibilities for an improved knowledge of upper-air conditions from the point of view of meteorological significance is an indication of a trend to the practical application of this field of investigation that heretofore had been chiefly of academic interest.

In cooperation with the United States Weather Bureau, the University of Chicago and other institutions, a wide distribution of cosmic-ray counters has been planned whose continuous recordings it is believed will furnish data of important meteorological significance.

The Chairman can report that the new Laboratory for Cosmic-Terrestrial Research at Needham, Massachusetts, in conjunction with Massachusetts Institute of Technology, has continued its observational work in field-strength determinations and atmospheric electricity in addition to cooperating in certain investigations of defense-agencies. The results of studies of some of the observational data in cosmic-terrestrial phenomena have been published during the year. Two papers which have been reported to the Union will be found printed elsewhere in the Transactions of 1942. Arrangements have been completed for stationing at this Laboratory one of the new cosmic-ray counters mentioned above with which the Massachusetts Institute of Technology will undertake its cooperative enterprise in this field with the University of Chicago and the United States Weather Bureau.

HARLAN T. STETSON, Chairman

APPENDIX I--REPORT OF THE COMMITTEE ON NATIONAL WELFARE AND RELATED FUNCTIONS

The following is a report of the first meeting of your Committee, held in Boston, December 30, 1941. Present: FIELD, MARBLE, MATHER, SNELGROVE, STETSON, THOM (of the Committee) and Vice-President ADAMS. This report is in terms of recommendations as to the functions of the Committee, subject to the approval of the Executive Committee of the Union and further consideration by the 16 members of the Committee not present at the Boston meeting.

Your Committee on National Welfare and Related Functions should have at this time a double objective: (a) The effective mobilization of the technical resources possessed by the members of the American Geophysical Union and the coordination of their activities toward the imperative task of winning the War, and (b) the greatest possible contribution toward the effective education

of the members of the Union and of the general public to the end that the United States may fulfill as completely as possible the great responsibility that will rest upon it for leadership in post-war world reconstruction. Both of these objectives entail research, the application of the results of research in practice, and education.

In connection with objective (a) due consideration therefore should be given to:

Technical assistance to the armed forces--Since the National Research Defense Committee has provided the organizational machinery for most effectively utilizing research possibilities from the point of view of National Defense, it would appear that the American Geophysical Union could best serve these interests by bringing to the attention of the National Research Defense Council suitable projects and personnel that may come to its attention. These would of course be instances where a liaison between members of the Union engaged in specific research projects of value to the National Defense has not yet been established.

In view of the varied interests of geophysics represented by the several Sections of the Union, and in view of the constant demand for physicists in connection with defense-projects, it may well be that the membership of the Union could provide competent investigators from fields allied to physics not yet thoroughly canvassed. It was suggested, therefore, that the officers of the several Sections of the Union be requested by the American Geophysical Union's Committee on National Welfare and Related Functions to survey the possibilities of further technical aid from their respective Sections. This Committee is aware of the fact that many are already engaged specifically in defense work from among research men in the various fields which the Union represents. It seems probable, however, that the possibilities have not been exhausted and that officers of Sections should be made acutely aware of the primary interests of National Defense in all fields of geophysics that may be useful to the Government.

The attainment of objective (a) also involves the specific training of individuals and groups for more efficient service on behalf of the armed forces.

Another educational project for which this Committee of the American Geophysical Union might consider itself especially well qualified to foster is the specific training of groups here and there in such fundamental basic technology of the Earth's sciences as should qualify competent individuals to be of special service to the National Defense; such, for example, as training in map-reading, geodesy, and navigation, as applied to the land, sea, and air. Courses of instruction in such specific topics might well be suggested by the Committee on National Welfare and Related Functions to various collegiate institutions of the country to the end that there may result a unified and concerted program of student education in the fields of Earth sciences above mentioned.

Objective (a) involves such items as the insistence upon continuity in fundamental research. Because of the large number of scientific men devoting a considerable share or the whole of their time to defense-projects, it is to be expected that much of the work in fundamental science in the country for the time being must be secondary to the demands of defense. For this very reason, therefore, it is believed that this Committee could be of very great help in bringing to the attention of the authorities concerned the need of continuing fundamental research in science to the greatest possible extent by those not immediately involved in defense-projects, and in recommending that budgets and appropriations for such work should not be sacrificed without the most thorough survey. This is particularly true in those fields where the continuity of observations of natural phenomena is paramount to the success of any later analyses that may have to be temporarily postponed due to the national emergency.

It is obvious, for example, that radio communication rests fundamentally upon our knowledge of the ionosphere and its changing behavior pattern with time. To interrupt, therefore, the continuity of routine ionospheric observations that have been maintained for years would be a serious detriment to fundamental research on the ionosphere which provides that basis upon which the prediction of communication conditions depends. Immediately involved likewise are the daily observations of solar activity maintained at the United States Naval Observatory. It was on the basis of these solar observations that the National Defense was forewarned of the anticipated disruptions of radio communications coincident with the atmospheric-electric disturbances of September 18, 1941.

Similarly, the continuation of magnetic observations at magnetic observatories now maintained by the Government or by private interests is of utmost importance because of the interrelationships between geomagnetism and the ionization of the upper atmospheric layers.

Observations of variations of latitude at the Gaithersburg Station of the United States Coast and Geodetic Survey while not immediately contributing to National Defense are so fundamental in solving certain basic problems in Earth science, such as the motion of the Earth's axis, that the interruption of this series of observations for even a year or two would leave serious gaps in the continuity of the coordinates of the pole that could at no subsequent time ever be retrieved. The reduction and analysis of these observations could well be postponed without serious inconvenience, but determination of such fundamental data, varying with the time coordinate, when once omitted becomes a serious loss that at no later time can ever be regained.

It is believed, therefore, that this Committee on National Welfare and Related Functions should be in position to advise the Government, through the National Research Council of which the American Geophysical Union is the official Committee on the Earth, relative to such fundamental observations in progress. The advice of this Committee should insure that those directly responsible for appropriations to scientific bureaus and departments shall have sufficient information so that such essential observations as have been mentioned shall not be interrupted.

Object (b) necessitates an effort to increase the sense of social responsibility of men of science with the hope that they will take a more active part in directing the use of the tools of science toward social reconstruction.

In these days of national emergency when all the resources of science are being marshalled for National Defense, an increasing responsibility becomes scientists and scientific bodies to foster by every available means special interest and special understanding for the aims and methods of science. It is still unfortunate that some otherwise intelligent groups of society look upon science as a source of the mechanical tyranny brought about in modern warfare. While science is not entirely to be blamed for the misuse of gadgets that have been created from the products of its workshops, science cannot dodge the responsibility of divulging its aims and methods which, on the other hand, have not only made for mankind's comfort and well-being, but have enlarged his intellectual horizon and understanding of the universe in which he lives. This Committee, therefore, should consider its responsibilities in the education of the public to the better interests not only of science but of society itself.

Coordinating as it does the work of scientists in such basic fields as those indicated by the various Sections, the American Geophysical Union is in a most strategic position to promote a better understanding of the relationship between man, society, and the physical environment provided by the Earth. Data might well be gathered to indicate the increasing dependence of man upon the resources of the Earth, the inescapable interdependence of men in the world society resulting from our use of resources that are unevenly distributed because of climatic variations and geologic structure, and the abundance of the world stores of raw materials in relation to the demand that mankind is likely to place upon them. Thanks to science and technology, we are now living in an age of plenty. Trained minds, habituated to scientific methods of thought, should prove of greatest value in the effort so to organize society on a world-wide basis that there may not only be efficiency and comfort, but also reasonable peace and security for all. Your Committee is, therefore, deeply concerned with the activities of the International Scientific Unions, especially in the Americas, and the remaining spheres of influence of the Allied Powers, and is preparing recommendations for specific and cooperative action particularly within the field of the Earth sciences. In these endeavors your Committee is assured the complete cooperation of the International Commission on Continental and Oceanic Structure.

R. M. FIELD, Chairman

APPENDIX J-a--MINUTES OF THE ANNUAL MEETING OF 1942, SECTION OF GEODESY, AMERICAN GEOPHYSICAL UNION

The Annual Meeting was held in Room 202, Hall of Government, George Washington University, 21st and G Streets, April 4, 1942. The meeting was called to order by the President, R. M. WILSON, at $09^{h}\ 25^{m}$. [For registered attendance, see Appendix A.]

The President called attention to the fact that the minutes of the Twenty-Second Annual Meeting held May 2, 1941, had been printed and sent out to the members and that no corrections had been received. The minutes were declared approved as printed and circulated.

The President called attention to the meetings of the American Congress on Surveying and Mapping to be held in Washington on April 16 and 17, 1942, and invited the members of the Section of Geodesy to attend these meetings.

The President stated that a resolution had been received but that it was too late to appoint a Committee on Resolutions and the resolution, therefore, would be held over until the next annual meeting.

The President requested everyone attending the meeting of the Section of Geodesy to register at the registration booth in the entrance lobby.

H. S. RAPPLEYE then called attention to the membership drive now in progress and stated that he had application blanks if anyone present was interested in becoming a member of the American Geophysical Union.

The Section then proceeded to hear the papers on the scientific program [printed in these Transactions, pp. 187-223].

The President stated that a paper entitled "Progress of geodetic work in Mexico," by Manuel Medina, had been received a few days before the meeting. This paper was written in Spanish and it was not possible to have it translated in time to be presented at the meeting but it will be printed in the Transactions.

To illustrate his paper on the prismatic astrolabe, Mr. SAMUELS had an astrolabe set up in the room and this was examined by the members of the Section at the close of the meeting.

The meeting adjourned at $12^h\ 18^m$.

WALTER D. SUTCLIFFE, Secretary

APPENDIX J-b--MINUTES OF THE ANNUAL MEETING OF 1942, SECTION OF SEISMOLOGY, AMERICAN GEOPHYSICAL UNION

The Annual Meeting was called to order by the President, H. E. McCOMB, at $09^h\ 30^m$, April 3, 1942, in Room 202, Hall of Government, George Washington University, Washington, D. C. [For registered attendance, see Appendix A.]

The minutes of the previous meeting having been published and no objections or corrections received, the President declared them approved.

The President announced that FRANK NEUMANN had been forced to resign as Secretary on account of ill health, and that ARCHIE BLAKE had been appointed to complete his term through June 30, 1942. Mr. NEUMANN was given a unanimous vote of thanks for his faithful service.

The President appointed a Nominating Committee, consisting of A. K. LUDY (Chairman), E. R. SHEPARD, and F. W. SOHON, S.J., to nominate a Secretary to serve from July 1, 1942, to June 30, 1945, inclusive. The Committee nominated ARCHIE BLAKE, who was unanimously elected.

The President appointed a Committee on Resolutions consisting of ARCHIE BLAKE (Chairman), L. V. JUDSON, and V. C. STECHSCHULTE, S.J. The Committee reported a resolution expressing appreciation to the Navy Department for the schedule of precise time-signals originating at the United States Naval Observatory and broadcast by the Navy Department from its various radio stations. This resolution was unanimously approved by the Section and transmitted to the Committee on Resolutions of the Union for adoption by the Union as a whole. [See p. 714 for resolution as adopted by the Union.]

There being no further business, the Section proceeded to the scientific papers [reported in these Transactions, pp. 227-233].

The meeting was adjourned at $11^h\ 35^m$.

ARCHIE BLAKE, Acting Secretary

APPENDIX J-c--MINUTES OF THE ANNUAL MEETING OF 1942, SECTION OF METEOROLOGY, AMERICAN GEOPHYSICAL UNION

The Twenty-Third Annual Meeting of the Section of Meteorology, President THORNTHWAITE presiding, was held from $09^h\ 15^m$ to $12^h\ 00^m$, April 3, 1942, in Room 101, Hall of Government, George Washington University. About 150 members and guests were in attendance. [For registered attendance, see Appendix A.]

The reading of the minutes of the previous meeting was dispensed with as they had already been published in the Transactions of 1941 and no corrections or additions had been received.

There was some discussion of the relations of the Section with the American Meteorological Society following remarks by President THORNTHWAITE in which Drs. HUMPHREYS and BROOKS participated.

L. P. HARRISON was appointed as a Committee to receive and edit resolutions. One resolution was proposed. It pertained to the reelection of certain present members as corresponding members on the basis of the recent changes in the Statutes and By-Laws of the Union. After discussion the proposed resolution was tabled as it appeared that its purpose was automatically cared for by the Statute itself and that no formal action need be taken by the Executive Committee under whose jurisdiction such an action would come.

R. H. WEIGHTMAN called attention to the large amount of labor involved in preparing for publication the Transactions and emphasized the need of increasing the membership of the Union in order to secure an adequate income to relieve the General Secretary of the arduous work he has gratuitously performed for several years. He suggested means of obtaining new members and hinted that there was nothing in the Statutes to prevent a member, when paying his dues, from including an additional amount as is the practice in the American Meteorological Society.

The scientific program was then presented. The papers, two of which had to be read by title for want of time, are printed in these Transactions on pages 237-286.

H. D. HARRADON, Secretary

APPENDIX J-d--MINUTES OF THE ANNUAL MEETING OF 1942, SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY, AMERICAN GEOPHYSICAL UNION

The Twenty-Third Annual Meeting of the Section of Terrestrial Magnetism and Electricity was called to order, in the absence of President E. A. ECKHARDT, by Vice-President H. F. JOHNSTON at $9^h\ 20^m$, April 4, 1942, in Room 101, Hall of Government, George Washington University, Washington, D. C. [For registered attendance, see Appendix A.]

In the absence of the Secretary, J. W. JOYCE, the Vice-President appointed O. W. SWAINSON to act as Secretary for the meeting.

The minutes of the previous Annual Meeting were declared approved as printed.

There was no old business to come before the Section.

The following motion was presented by Dr. H. H. HOWE: That a Committee on Units be appointed for the purpose of examining into magnetic units and submitting recommendations to the next meeting. The motion was seconded and carried. No further action was taken at the time of the meeting.

There being no further business, the Section proceeded to the scientific program and the papers published in these Transactions were presented [pp. 289-315].

The meeting was adjourned at $12^h\ 10^m$.

O. W. SWAINSON, Secretary Pro-tem.

APPENDIX J-e--MINUTES OF THE ANNUAL MEETING OF 1942, SECTION OF OCEANOGRAPHY, AMERICAN GEOPHYSICAL UNION

The Annual Meeting of the Section of Oceanography was held at Washington, D. C., Friday, April 3, 1942, in Room 202, Hall of Government, George Washington University. The meeting was called to order by Captain PAUL C. WHITNEY, President, at $14^h\ 00^m$. [For registered attendance, see Appendix A.]

The minutes of the last Annual Meeting were approved as published. With the consent of Admiral G. S. BRYAN, the second paper of the printed program was given first because Captain E. H. SMITH, who read it for Admiral R. R. WAESCHE, had an urgent appointment to keep. This and the other papers presented are published on pages 319-338 of these Transactions.

Following Admiral COLBERT'S paper, Mr. MARMER contributed some remarks about his recent visit to Latin America. Mr. MASON'S paper was discussed by Dr. SCHMITT and others. T. H. WHITCROFT'S paper was discussed by several members. MILTON J. LOBELL'S paper was discussed at some length by Dr. ROBERT CUSHMAN MURPHY, who had recently returned from the west coast of South America. Dr. MURPHY'S paper was discussed by Captain WHITNEY, Captain GARNER, Mr. MARMER, and Dr. SCHMITT. A number of questions were asked of Dr. MURPHY by the members and guests present.

The meeting adjourned at $16^h\ 45^m$.

WALDO L. SCHMITT, Secretary

APPENDIX J-f--MINUTES OF THE ANNUAL MEETING OF 1942, SECTION OF VOLCANOLOGY, AMERICAN GEOPHYSICAL UNION

The Annual Meeting of the Section of Volcanology was held in Room 203, Hall of Government, George Washington University, Washington, D. C. The morning session was called to order by President A. F. BUDDINGTON at $09^h\ 15^m$. The reading of the minutes of the previous meeting was dispensed with as they had been published in the Transactions of 1941. The Secretary reminded the members of the importance of assisting the present membership drive in every way possible as Volcanology had been poorly represented among the newly elected members. [For registered attendance, see pp. 716-718.]

The scientific papers were presented as published in these Transactions [pp. 341-347]. The paper by GAULT was discussed by BUDDINGTON, JAHNS' paper was discussed by KOSCHMAN, INGERSON, GRATON, KESLER, and BUDDINGTON, and BALK'S paper by JAHNS, A. C. SPENCER, GRATON, INGERSON, LOVERING, and KESLER. The paper by LOCKE was read at the end of the morning session by BUDDINGTON in LOCKE'S absence, and was discussed by LOVERING, CLOOS, KOSCHMAN, Mrs. STOSE, and GRATON; it was regretted that the author was unable to be present to answer some of the questions raised. The morning session adjourned at $12^h\ 25^m$.

The afternoon session was called to order at $14^h\ 10^m$ by President BUDDINGTON. PARSON'S paper was discussed by GRATON; STEPHENSON'S by SPENCER, FISCHER, FAHEY, C. S. ROSS, GRATON, BUDDINGTON, and WAYLAND; BUDDINGTON'S by STEPHENSON, GRATON, SPENCER, and FISCHER; JENSEN'S by GRATON; and COATS' by C. S. ROSS.

The meeting adjourned at $16^h\ 20^m$.

JOHN S. VHAY, Secretary

APPENDIX J-g--MINUTES OF THE ANNUAL MEETING OF 1942, SECTION OF HYDROLOGY, AMERICAN GEOPHYSICAL UNION

The Section of Hydrology held three sessions at George Washington University on April 3 and 4, and a round-table discussion in the North Building, Department of the Interior, on April 4, 1942. [For registered attendance, see pp. 716-718.]

The first session was called to order at $09^h\ 20^m$, April 3, by President GROVER. The minutes of the Annual Meeting of 1941, as published in the Transactions of 1941 [p. 577], were approved. Mr. HERTZLER, as Chairman of the Nominating Committee, presented the following

nominations: For President, J. E. CHURCH; for Vice-President, L. G. STRAUB; for Secretary, K. H. BEIJ. It was moved and seconded that the President cast a unanimous ballot for the nominees. The motion was carried, and the President declared the nominees elected. A vote of appreciation to the retiring officers was passed. Dr. MEINZER, Chairman of the Committee on a volume of Hydrology to be published by the National Research Council, reported that the entire volume of 705 pages was in page-proof and would be printed in a few weeks. Nine papers and the reports of four Research and Special Committees were presented. The session adjourned at noon.

The second session was called to order at 16^h, April 3, by President GROVER. Nine papers and the reports of eight Research and Special Committees were presented. The session adjourned at 17^h.

The third session was called to order at $09^h\ 15^m$, April 4, by President GROVER. Ten papers and the reports of one Research and one Special Committee were presented. The session adjourned at $12^h\ 30^m$.

R. A. HERTZLER, Acting Secretary, prepared minutes of the round-table session as follows: The round-table discussion was opened at 14^h, April 4, in Room 5242, North Interior Building, by President GROVER.

The President announced that he had appointed recently a Committee consisting of C. F. MERRIAM, Chairman, W. G. HOYT, and K. H. BEIJ, to cooperate with similar committees of the other Sections in obtaining funds for the JOHN A. FLEMING Publication Fund. The following resolution presented by C. S. JARVIS was passed unanimously:

WHEREAS, The cost of publishing this year's Transactions is estimated to be greater than the funds available, and this group agrees that the best way to raise the money for publishing the Transactions is by direct assessment, therefore, be it

RESOLVED, That those present will contribute two dollars ($2.00), preferably more, but not less than one dollar ($1.00), each, to help defray the cost of publishing the Transactions; and that this amount will be contributed, in addition to annual dues, at the time the annual dues are paid.

After discussion of the need for conducting hydrologic investigations and maintaining unbroken records throughout the War, the President was authorized to draft a resolution expressing the viewpoint of the Section of Hydrology concerning this matter. The President appointed as his assistants: R. S. GOODRIDGE; O. E. MEINZER; and R. A. HERTZLER. [See p. 714 for this resolution in final form as adopted by the Union.]

Upon request, W. G. HOYT agreed to convey the greetings of the group to A. C. LANE, a pioneer in the science of hydrology and the only living member of the first "school" for stream-gaging in the United States which was conducted by the Geological Survey.

The next topic discussed was the relation of flood-crest discharges as measured by the usual current-meter procedure to those calculated as flow over spillways and through dams.

R. E. HORTON'S paper "An experiment on flow through a capillary tube" was discussed by many of the members. It was agreed that the Chairman of the Program Committee should send a copy of HORTON'S final manuscript to O. E. MEINZER who will prepare a discussion for the Transactions. The discussion turned to the flow of water through soils and to the separation of ground-water flow from the hydrograph during which evidence of accretion as well as depletion of ground-water flow during a flood-rise was presented. With the thought of coordinating the views of the "ground-water hydrologists" with those of the "surface-water hydrologists", C. R. HURSH extended a cordial invitation to visit the Coweeta Experimental Forest where data pertaining to surface and sub-surface waters are collected.

The last subject for discussion was snow-quality, particularly W. T. WILSON'S paper, "Some observations on the thermal quality of snow."

The meeting was adjourned at $16^h\ 30^m$. Approximately 35 members attended.

The papers and reports of Committees are published in these Transactions [see pp. 353-693].

K. HILDING BEIJ, Secretary

APPENDIX J-h--MINUTES OF THE ANNUAL MEETING OF 1942, SECTION OF TECTONOPHYSICS, AMERICAN GEOPHYSICAL UNION

The Annual Meeting of the Section of Tectonophysics of the American Geophysical Union was held in Room 101, Hall of Government, George Washington University, on April 3, 1942. The meeting was called to order by President L. H. ADAMS at $14^h\ 08^m$. A brief business meeting preceded the presentation of papers. There was no old business upon which action was needed. The only new business was the election of a Secretary, which was made necessary by the resignation of DAVID GRIGGS, whose term expires June 30, 1943. EARL INGERSON, of the Geophysical Laboratory, was elected to serve for the remainder of the term. [For registered attendance, see pp. 716-718.]

The scientific session was a Symposium and Conference on the Mechanics of flow and crustal deformation. The papers presented and discussed appear on pages 697-710 of these Transactions.

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